Biopower

Technology Description

Biopower, also called biomass power, is the generation of electric power from biomass resources – now usually urban waste wood, crop and forest residues; and, in the future, crops grown specifically for energy production. Biopower reduces most emissions (including emissions of greenhouse gases-GHGs) compared with fossil fuel-based electricity. Since biomass absorbs CO_2 as it grows, the entire biopower cycle of growing, converting to electricity, and regrowing biomass can result in very low CO_2 emissions. Through the use of residues, biopower systems can even represent a net sink for GHG emissions by avoiding methane emissions that would result from landfilling of the unused biomass.

Representative Technologies for Conversion of Feedstock to Fuel for Power and Heat

• *Homogenization* is a process by which feedstock is made physically uniform for further processing or for combustion. (includes chopping, grinding, baling, cubing, and pelletizing)

• *Gasification* (via pyrolysis, partial oxidation, or steam reforming) converts biomass to a fuel gas that can be substituted for natural gas in combustion turbines or reformed into H_2 for fuel cell applications.

• *Anaerobic digestion* produces biogas that can be used in standard or combined heat and power (CHP) applications. Agricultural digester systems use animal or agricultural waste. Landfill gas also is produced anaerobically.

• *Biofuels production for power and heat* provides liquid-based fuels such as methanol, ethanol, hydrogen, or biodiesel.

Representative Technologies for Conversion of Fuel to Power and Heat

• Direct combustion systems burn biomass fuel in a boiler to produce steam that is expanded in a Rankine Cycle prime mover to produce power.

• Cofiring substitutes biomass for coal or other fossil fuels in existing coal-fired boilers.

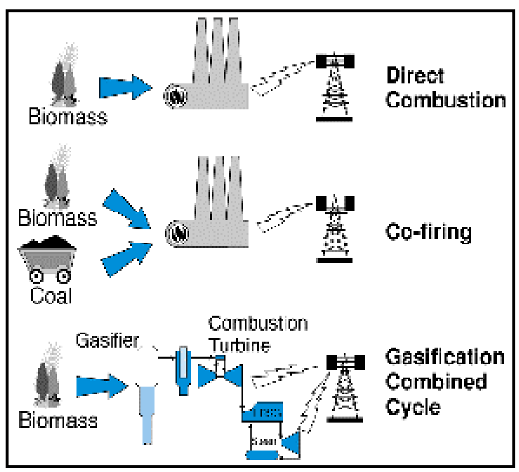
• Biomass or biomass-derived fuels (e.g. syngas, ethanol, biodiesel) also can be burned in combustion turbines (Brayton cycle) or engines (Otto or Diesel cycle) to produce power.

• When further processed, biomass-derived fuels can be used by fuels cells to produce electricity

System Concepts

• CHP applications involve recovery of heat for steam and/or hot water for district energy, industrial processes, and other applications.

• Nearly all current biopower generation is based on **direct combustion** in small, biomass-only plants with relatively low electric efficiency (20%), although total system efficiencies for CHP can approach 90%. Most biomass direct-combustion generation facilities utilize the basic Rankine cycle for electric-power generation, which is made up of the steam generator (boiler), turbine, condenser, and pump.



• For the near-term, **cofiring** is the most cost-effective of the power-only technologies. Large coal steam plants have electric efficiencies near 33%. The highest levels of coal cofiring (15% on a heat input basis) require separate feed preparation and injection systems.

• Biomass **gasification combined cycle** plants promise comparable or higher electric efficiencies (> 40%) using only biomass because they involve gas turbines (Brayton cycle), which are more efficient than Rankine cycles. Other technologies being developed include integrated gasification/fuel cell and biorefinery concepts.

Technology Applications

• The existing biopower sector, nearly 1,000 plants, is mainly comprised of direct-combustion plants, with an additional small amount of cofiring (six operating plants). Plant size averages 20 MW_e, and the biomass-to-electricity conversion efficiency is about 20%. Grid-connected electrical capacity has increased from less than 200 MW_e in 1978 to over 6500 MW_e in 2000. More than 75% of this power is generated in the forest products industry's CHP applications for process heat. Wood-fired systems account for close to 95% of this capacity. In addition, about 3,300 MW_e of municipal solid waste and landfill gas generating capacity exists. Recent studies estimate that on a life-cycle basis, existing biopower plants represent an annual net carbon sink of 4 MMTCe. Prices generally range from 8¢/kWh to 12¢/kWh.

Current Status

• CHP applications using a waste fuel are generally the most cost-effective biopower option. Growth is limited by availability of waste fuel and heat demand.

• Biomass cofiring with coal ($50 - 250/kW of biomass capacity) is the most near-term option for large-scale use of biomass for power-only electricity generation. Cofiring also reduces sulfur dioxide and nitrogen oxide emissions. In addition, when cofiring crop and forest-product residues, GHG emissions are reduced by a greater percentage (e.g. 23% GHG emissions reduction with 15% cofiring).

• Biomass gasification for large-scale (20 - 100MW_e) power production is being commercialized. It will be an important technology for cogeneration in the forest-products industries (which project a need for biomass and black liquor CHP technologies with a higher electric-thermal ratio), as well as for new baseload capacity. Gasification also is important as a potential platform for a biorefinery.

• Small biopower and biodiesel systems have been used for many years in the developing world for electricity generation. However, these systems have not always been reliable and clean. DOE is developing systems for village-power applications and for developed-world distributed generation that are efficient, reliable, and clean. These systems range in size from 3kW to 5MW and will begin field verification in the next 1-3 years.

• Current companies include:

Future Energy Resources, Inc. (FERCO)	Foster Wheeler
Energy Products of Idaho	PRM Energy Systems

Technology History

• In the latter part of the 19th century, wood was the primary fuel for residential, commercial, and transportation uses. By the 1950s, other fuels had supplanted wood. In 1973, wood use had dropped to 50 million tons per year.

• At that point, the forest products and pulp and paper industries began to use wood with coal in new plants and switched to wood-fired steam power generation.

• The Public Utility Regulatory Policies Act (PURPA) of 1978 stimulated the development of nonutility cogeneration and small-scale plants, leading to 70% self-sufficiency in the wood processing and pulp-and-paper sectors.

• As incentives were withdrawn in the late 1980s, annual installations declined from just more than 600 MW in 1989, to 300-350MW in 1990.

• There are now nearly 1,000 wood-fired plants in the United States, with about two-thirds of those providing power (and heat) for on-site uses only.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for Biomass Direct-fired and Gasification configurations are projected to be:

	2000	2010	2020
Direct-fired	7.5	7.0	5.8
Gasification	6.7	6.1	5.4

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997.

- R&D Directions include:

Gasification – This technology requires extensive field verification in order to be adopted by the relatively conservative utility and forest-products industries, especially to demonstrate integrated operation of biomass gasifier with advanced-power generation (turbines and/or fuel cells). Integration of gasification into a biorefinery platform is a key new research area.

Small Modular Systems – Small-scale systems for distributed or minigrid (for premium or village power) applications will be increasingly in demand.

Cofiring – The DOE biopower program is moving away from research on cofiring, as this technology has reached a mature status. However, continued industry research and field verifications are needed to address specific technical and nontechnical barriers to cofiring. Future technology development will benefit from finding ways to better prepare, inject, and control biomass combustion in a coal-fired boiler. Improved methods for combining coal and biomass fuels will maximize efficiency and minimize emissions. Systems are expected to include biomass cofiring up to 5% of natural gas combined-cycle capacity.

Biomass

Market Data

Cumulative Generating Capability, by Type (MW)	*Source: Energy Information Administration (EIA), Annual Energy Review 2001, Tables 8.7b and 8.7c, and world data from United Nations Development Program, World Energy Assessment, 2000, Table 7.25.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S. Electric Power Sector										
Municipal Solid Waste[1]	NA	200	1,900	2,700	2,600	2,500	2,600	2,600	2,800	2,800
Wood and Other Biomass[2]	100	200	1,000	1,500	1,400	1,500	1,400	1,500	1,500	1,500
U.S. Cogenerators[3]										
Municipal Solid Waste[1]			600	700	900	1,000	1,100	1,100	1,100	1,100
Wood and Other Biomass[2]			4,500	5,300	5,400	5,400	5,400	5,400	4,600	4,700
U.S. Total										
Municipal Solid Waste[1]	NA	200	2,500	3,400	3,500	3,500	3,700	3,700	3,900	3,900
Wood and Other Biomass[2]	100	200	5,500	6,800	6,800	6,900	6,800	6,900	6,100	6,200
Biomass Total	100	400	8,000	10,200	10,300	10,400	10,500	10,600	10,000	10,100
Rest of World Total[4]							29,500			
World Total							40,000			

[1] Municipal solid waste, landfill gas, sludge waste, tires, agricultural byproducts, and other biomass.
[2] Wood, black liquor, and other wood waste.
[3] Data include electric power sector and end-use sector (industrial and commercial) generators.
[4] Number derived from subtracting U.S. total from the world total. Figures may not add due to rounding.

U.S. Annual Installed Generating Capability, by Type (MW)	*Source: Renewable Electric Plant Information System (REPiS), Version 7, NREL, 2003.*										
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Agricultural Waste[1]	22.6	20.1	0.0	4.0	0.0	21.6	0.0	0.0	0.0	0.0	0.0
Biogas[2]	0.1	58.6	49.8	17.5	74.8	95.6	91.1	107.6	27.7	57.8	16.0
Municipal Solid Waste[3]	50.0	117.2	260.3	94.5	0.0	0.0	0.0	22.0	0.0	0.0	0.0
Wood Residues[4]	260.4	254.8	299.4	66.5	91.6	40.0	90.3	13.0	0.0	11.3	13.8
Total	333.0	450.7	609.5	182.5	166.4	157.2	181.4	142.6	45.9 [5]	69.1	29.8

U.S. Cumulative Generating Capability, by Type[6] (MW)	*Source: Renewable Electric Plant Information System (REPiS), Version 7, NREL, 2003.*										
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Agricultural Waste[1]	40	92	165	351	351	373	373	373	373	373	373
Biogas[2]	18	117	359	525	600	695	786	894	922	979	995
Municipal Solid Waste[3]	263	697	2,172	2,948	2,948	2,948	2,948	2,970	2,970	2,970	2,970
Wood Residues[4]	3,576	4,935	6,306	7,212	7,304	7,344	7,434	7,447	7,447	7,458	7,472
Total	3,897	5,840	9,002	11,036	11,202	11,360	11,541	11,684	11,711	11,780	11,810

Note: The data in this table does not match data in the previous table due to different coverage ratios in EIA and REPIS databases.

[1]Agricultural residues, cannery wastes, nut hulls, fruit pits, nut shells

[2]Biogas, alcohol (includes butahol, ethanol, and methanol), bagasse, hydrogen, landfill gas, livestock manure, wood gas (from wood gasifier)

[3]Municipal solid waste (includes industrial and medical), hazardous waste, scrap tires, wastewater sludge, refuse-derived fuel

[4]Timber and logging residues (Includes tree bark, wood chips, saw dust, pulping liquor, peat, tree pitch, wood or wood waste)

[5] Includes 18.2 MW of unspecified biomass resources

[6] There are an additional 65.45 MW of Ag Waste, 5.476 MW of Bio Gas and 483.31 MW of Wood Residues that are not accounted for here because they have no specific online date.

Generation from Cumulative Capacity, by Type (Million kWh)	*Source: EIA, Annual Energy Review 2001, Tables 8.2b and 8.2c, and world data from United Nations Development Program, World Energy Assessment, 2000, Table 7.25.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S. Electric Power Sector										
Municipal Solid Waste[1]	158	640	10,245	16,326	16,078	16,397	16,963	17,112	17,592	17,125
Wood and Other Biomass[2]	275	743	5,327	5,885	6,493	6,468	6,644	7,254	7,301	7,229
U.S. Cogenerators[3]										
Municipal Solid Waste[1]			2,900	4,079	4,834	5,312	5,485	5,460	5,541	5,643
Wood and Other Biomass[2]			24,629	30,636	30,307	30,480	29,694	29,787	30,294	29,643
U.S. Total										
Municipal Solid Waste[1]	158	640	13,145	20,405	20,911	21,709	22,448	22,572	23,133	22,768
Wood and Other Biomass[2]	275	743	29,956	36,521	36,800	36,948	36,338	37,041	37,595	36,872
Biomass Total	433	1,383	43,101	56,926	57,712	58,658	58,786	59,613	60,728	59,640
Rest of World Total[4]							101,214			
World Total							160,000			

[1] Municipal solid waste, landfill gas, sludge waste, tires, agricultural byproducts, and other biomass.
[2] Wood, black liquor, and other wood waste.
[3] Data include electric power sector and end-use sector (industrial and commercial) generators.
[4] Number derived from subtracting U.S. total from the world total. Figures may not add due to rounding.

U.S. Annual Energy Consumption for Electricity Generation (Trillion Btu)	*Source: EIA, Annual Energy Review 2001, Tables 2.2b and 2.2c*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Electric-Power Sector	5.0	15.0	280.0	388.0	397.0	409.0	412.0	415.0	420.0	418.0
Commercial Sector[1]			16.5	22.3	32.1	34.3	32.7	33.5	26.5	25.8
Industrial Sector[1]			315.3	385.3	407.1	380.7	362.0	373.0	378.8	364.9
Total Biomass	5.0	15.0	611.7	795.6	836.2	824.0	806.7	821.5	825.2	808.7

Data include wood (wood, black liquor, and other wood waste) and waste (municipal solid waste, landfill gas, sludge waste, tires, agricultural byproducts, and other biomass).
[1] Data includes combined-heat-and-power (CHP) and electricity-only plants.

Technology Performance

Source: Renewable Energy Technology Characterizations, EPRI TR-109496, 1997 (this document is currently being updated by DOE and the values most likely will change).

Efficiency		1980	1990	1995[1]	2000	2005	2010	2015[2]	2020
Capacity Factor (%)	Direct-fired			80.0	80.0	80.0	80.0	80.0	80.0
	Cofired			85.0	85.0	85.0	85.0	85.0	85.0
	Gasification			80.0	80.0	80.0	80.0	80.0	80.0
Efficiency (%)	Direct-fired			23.0	27.7	27.7	27.7	30.8	33.9
	Cofired			32.7	32.5	32.5	32.5	32.5	32.5
	Gasification			36.0	36.0	37.0	37.0	39.3	41.5
Net Heat Rate (kJ/kWh)	Direct-fired			15,280	13,000	13,000	13,000	11,810	10,620
	Cofired			11,015	11,066	11,066	11,066	11,066	11,066
	Gasification			10,000	10,000	9,730	9,730	9,200	8,670

Cost		1980	1990	1995[1]	2000	2005	2010	2015	2020
Total Capital Cost ($/kW)	Direct-fired			1,965	1,745	1,510	1,346	1,231	1,115
	Cofired[3]			272	256	241	230	224	217
	Gasification			2,102	1,892	1,650	1,464	1,361	1,258
Feed Cost ($/GJ)	Direct-fired			2.50	2.50	2.50	2.50	2.50	2.50
	Cofired[3]			-0.73	-0.73	-0.73	-0.73	-0.73	-0.73
	Gasification			2.50	2.50	2.50	2.50	2.50	2.50
Fixed Operating Cost ($/kW-yr)	Direct-fired			73.0	60.0	60.0	60.0	54.5	49.0
	Cofired[3]			10.4	10.1	9.8	9.6	9.5	9.3
	Gasification			68.7	43.4	43.4	43.4	43.4	43.4

		1980	1990	1995[1]	2000	2005	2010	2015	2020
Variable Operating Costs ($/kWh)	Direct-fired			0.009	0.007	0.007	0.007	0.006	0.006
	Cofired[3]			-0.002	-0.002	-0.002	-0.002	-0.002	-0.002
	Gasification			0.004	0.004	0.004	0.004	0.004	0.004
Total Operating Costs ($/kWh)	Direct-fired			0.055	0.047	0.047	0.047	0.043	0.039
	Cofired[3]			-0.008	-0.008	-0.008	-0.009	-0.009	-0.009
	Gasification			0.040	0.036	0.036	0.036	0.034	0.033
Levelized Cost of Energy ($/kWh)	Direct-fired			0.087	0.075		0.070		0.058
	Cofired[3]			N/A	N/A	N/A	N/A	N/A	N/A
	Gasification			0.073	0.067		0.061		0.054

[1] Data is for 1997, the base year of the Renewable Energy Technology Characterizations analysis.

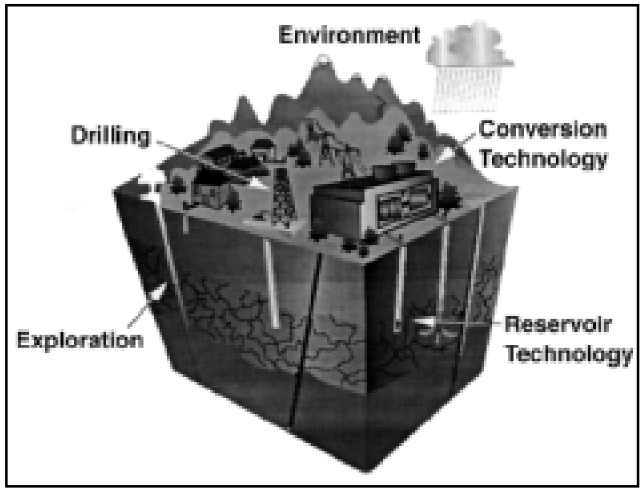
[2] Number derived by interpolation.

[3] Note cofired cost characteristics represent only the biomass portion of costs for capital and incremental costs above conventional costs for Operations & Maintenance (O&M), and assume \$9.14/dry tonne biomass and \$39.09/tonne coal, a heat input from biomass at 19,104 kJ/kg, and that variable O&M includes an SO_2 credit valued at \$110/tonne SO_2. No cofiring COE is reported in the *RETC*.

Geothermal Energy

Technology Description

Geothermal energy is thermal energy from within the earth. Hot water and steam are used to produce electricity or applied directly for space heating and industrial processes. There is potential to use geothermal energy to recover minerals and metals present in the geothermal brine.



System Concepts
- Geophysical, geochemical, and geological exploration locate permeable hot reservoirs to drill.
- Wells are drilled into the reservoirs.
- Well fields and distribution systems allow the hot geothermal fluids to move to the point of use, and are injected back to the earth.
- Steam turbines using natural steam or hot water flashed to steam, and binary turbines produce mechanical power that is converted to electricity.
- Direct applications utilize the thermal energy directly, for heating, without conversion to another form of energy.

Representative Technologies
- Dry-steam plants, which use geothermal steam to spin turbines;
- Flash-steam plants, which pump deep, high-pressure hot water into lower-pressure tanks and use the resulting flashed steam to drive turbines.
- Binary-cycle plants, which use moderately hot geothermal water to heat a secondary fluid with a much lower boiling point than water. This causes the secondary fluid to flash to vapor, which then drives the turbines.
- Exploration technologies for the identification of fractures and geothermal reservoirs; drilling to access the resource; geoscience and reservoir testing and modeling to optimize production and predict useful reservoir lifetime.

Technology Applications

- Mile-or-more-deep wells can be drilled into underground reservoirs to tap steam and very hot water that drive turbines and electricity generators. Because of economies of scale, geothermal power plants supply power directly to the grid, typically operating as baseload plants.
- Another use is direct applications to use the heat from geothermal fluids without conversion to electricity. In the United States, most geothermal reservoirs are located in the western states, Alaska, and Hawaii, but some eastern states have geothermal resources that are used for direct applications. Hot water near the Earth's surface can be piped directly into facilities and used to heat buildings, grow plants in greenhouses, dehydrate onions and garlic, heat water for fish farming, and pasteurize milk. Some cities pipe the hot water under roads and sidewalks to melt snow. District heating systems use networks of piped hot water to heat many buildings in a community.
- The recovery of minerals and metals from geothermal brine can add value to geothermal-power projects

Current Status

- Hydrothermal reservoirs provide the heat for about 2100 MW of operating generating capacity in the United States at 18 resource sites. Another 700 MW of capacity at The Geysers was shut down.
- Three types of power plants are operating today: dry steam, flash steam, and binary.
- Worldwide installed capacity stands at about 8000 MW.
- The United States has a resource base capable of supplying heat for 40 GW of electrical capacity at costs competitive with conventional systems.
- Hydrothermal reservoirs are being used to produce electricity with an online availability of 97%; advanced energy conversion technologies are being implemented to improve plant thermal efficiency.
- Direct applications capacity is about 600 MW_t in the United States.
- Direct-use applications are successful, but require colocation of a quality heat source and need.
- More than 20 states use the direct use of geothermal energy, including Georgia and New York.
- Current leading geothermal technology companies include the following:

Calpine Corporation
Caithness Energy
Cal Energy Company (a subsidiary of Mid American Energy Holding Company)
Ormat International, Inc.

Technology History

- The use of geothermal energy as a source of hot water for spas dates back thousands of years.
- In 1892, the world's first district heating system was built in Boise, Idaho, as water was piped from hot springs to town buildings. Within a few years, the system was serving 200 homes and 40 downtown businesses. Today, the Boise district heating system continues to flourish. Although no one imitated this system for nearly 70 years, there are now 17 district heating systems in the United States and dozens more around the world.
- United States' first geothermal power plant went into operation in 1922 at The Geysers in California. The plant was 250 kW, but fell into disuse.
- In 1960, the country's first large-scale geothermal electricity-generating plant began operation. Pacific Gas and Electric operated the plant, located at The Geysers. The resource at the Geysers is dry steam. The first turbine produces 11 megawatts (MW) of net power and operated successfully for more than 30 years.
- In 1979, the first electrical development of a water-dominated geothermal resource occurred at the East Mesa field in the Imperial Valley in California.
- In 1980, UNOCAL built the country's first flash plant, generating 10 MW at Brawley, California.
- In 1981, with a supporting loan from DOE, Ormat International, Inc., successfully demonstrated binary technology in the Imperial Valley of California. This project established the technical feasibility of larger-scale commercial binary power plants. The project was so successful that Ormat repaid the loan within a year.
- By the mid 1980s, electricity was being generated by geothermal power in four western states: California, Hawaii, Utah, and Nevada.
- In the 1990s, the U.S. geothermal industry focused its attention on building power plants overseas, with major projects in Indonesia and the Philippines.
- In 1997, a pipeline began delivering treated municipal wastewater and lake water to The Geysers steamfield in California, increasing the operating capacity by 70 MW.
- In 2000, DOE initiated its GeoPowering the West program to encourage development of geothermal resources in the western United States by reducing nontechnical barriers.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for the two major future geothermal energy configurations are projected to be:

	2000	2010	2020
Hydrothermal Flash	3.0	2.4	2.1
Hydrothermal Binary	3.6	2.9	2.7

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997.

- New approaches to utilization will be developed, which increase the domestic resource base by a factor of 10.
- Improved methodologies will be developed for predicting reservoir performance and lifetime.
- Advances will be made in finding and characterizing underground permeability and developing low-cost, innovative drilling technologies.
- Further R&D will reduce capital and operating costs and improve the efficiency of geothermal conversion systems.
- Heat recovery methods will be developed that allow the use of geothermal areas that are deeper, less permeable, or dryer than those currently considered as resources.

Geothermal

Market Data

Cumulative Installed Capacity	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001
Electricity (MW_e)										
U.S.	900	1,600	2,700	3,000	2,900	2,900	2,900	2,800	2,800	2,800
Rest of World	1,200	3,164	3,132	3,797		5,121	5,339		5,174	
World Total	2,100	4,764	5,832	6,797		8,021	8,239		7,974	
Direct-Use Heat (MW_{th})										
U.S.						1,905				
Rest of World						7,799				
World Total	1,950	7,072	8,064	8,664		9,704	11,000		17,175	

Source: U.S. electricity data from EIA - Annual Energy Review 2001, Table 8.7a; world totals from Renewable Energy World/July-August 2000 page 123, Table 1; 1998 world totals from UNDP World Energy Assessment 2000, Tables 7.20 and 7.25; 1997 world electricity and US and world direct-use heat data from Stefansson and Fridleifsson 1998, "Geothermal Energy: European and World-wide Perspective."

Cumulative Installed Capacity	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001
Electricity (MW_e)										
U.S.			2,775	2,817					2,228	
Rest of World			3,057	4,016					5,746	
World Total			5,832	6,833					7,974	
Direct-Use Heat (MW_{th})										
U.S.				1,874					3,766	
Rest of World				6,730					11,379	
World Total				8,604					15,145	

Source: International Geothermal Association, http://iga.igg.cnr.it/index.php

Annual Installed Electric Capacity (MW_e)	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002
U.S.	251.0	352.9	48.6	0	36.0	0	0	0	59.9	0	0

Source: Renewable Energy Project Information System (REPiS), Version 7, NREL, 2003.

Cumulative Installed Electric Capacity (MW_e)	*Source: Renewable Energy Project Information System (REPiS), Version 7, NREL, 2003.*										
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
U.S.	802	1,698	2,540	2,684	2,720	2,720	2,720	2,720	2,779	2,779	2,779

Installed Capacity and Power Generation/Energy Production from Installed Capacity

Source: Lund and Freeston, World-Wide Direct Uses of Geothermal Energy 2000, Lund and Boyd, Geothermal Direct-Use in the United States Update: 1995-1999, J. Lund, World Status of Geothermal Energy Use Overview 1995-1999 http://www.geothermie.de/europaundweltweit/Lund/wsoge_index.htm, Sifford and Blommquist, Geothermal Electric Power Production in the United States: A Survey and Update for 1995-1999, and G. Huttrer, The Status of World Geothermal Power Generation 1995-2000. Proceedings of the World Geothermal Congress 2000 http://geothermal.stanford.edu/wgc2000/SessionList.htm, Kyushu-Tohoku, Japan, May 28- June10, 2000.

Cumulative Installed Capacity	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Electricity (MW_e)									
U.S.				2,369	2,343	2,314	2,284	2,293	2,228
Rest of World				4,464					5,746
World Total	3,887	4,764	5,832	6,833					7,974
Direct-Use Heat* (MW_{th})									
U.S.									4,200
Rest of World									12,975
World Total	1,950	7,072	8,064	8,664				16,209	17,175

Annual Generation/Energy Production from Cumulative Installed Capacity	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Electricity (Billion kWh_e)									
U.S.				14.4	15.1	14.6	14.7	15.0	15.5
Rest of World									33.8
World Total									49.3
Direct-Use Heat* (TJ)									
U.S.				13,890				20,302	21,700
Rest of World				98,551				141,707	
World Total		86,249		112,441				162,009	185,139

* Direct-use heat includes geothermal heat pumps as well as traditional uses. Geothermal heat pumps account for 1854 MW_{th} (14,617 TJ) in 1995 and 6849 MW_{th} (23,214 TJ) in 1999 of the world totals and 3600 MW_{th} (8,800 TJ) in 2000 of the U.S. total. Conversion of GWh to TJ is done at 1TJ = 0.2778 GWh.

Annual Generation from Cumulative Installed Capacity	*Source: U.S. electricity data from EIA - Annual Energy Review 2001, Table 8.2a; world electricity totals from Renewable Energy World/July-August 2000, page 126, Table 2; 1998 world totals from UNDP World Energy Assessment 2000, Table 7.25; 1997 world electricity and US and world direct-use heat data from Stefansson and Fridleifsson 1998, "Geothermal Energy: European and World-wide Perspective."*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Electricity (Billion kWh_e)										
U.S.	5.1	9.3	14.9	13.4	14.3	14.7	14.8	14.8	14.1	13.8
Rest of World	8.9	7.7	4.1	6.6		29.0	31.2		35.2	
World Total	14	17	19	20		43.8	46		49.3	
Direct-Use Heat (billion kWh_{th})										
U.S.				3.9		4.0			5.6	
Rest of World				27.4		31.1			47.3	
World Total				31.2		35.1	40		53.0	

Annual U.S. Geothermal Heat Pump Shipments, by type (units)	*Source: EIA – Renewable Energy Annual 2001- Table 37.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
ARI-320				4,696	4,697	7,772	10,510	7,910	7,808
ARI-325/330				26,800	25,697	28,335	26,042	31,631	26,219
Other non-ARI Rated				838	991	1,327	1,714	2,138	1,554
Totals				32,334	31,385	37,434	38,266	41,679	35,581

Capacity of U.S. Heat Pump Shipments* (Rated Tons)	*Source: EIA – Renewable Energy Annual 2001- Table 38.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
ARI-320				13,120	15,060	24,708	35,776	27,970	26,469
ARI-325/330				113,925	92,819	110,186	98,912	153,947	130,132
Other non-ARI Rated				3,935	5,091	6,662	6,758	9,735	7,590
Totals				130,980	112,970	141,556	141,446	191,651	164,191

* One Rated Ton of Capacity equals 12,000 Btu's.

Annual U.S. Geothermal Heat Pump Shipments by Customer Type and Model Type (units)	*Source: EIA – Renewable Energy Annual 2001- Table 40, REA 2000 Table 38, REA 1999 Table 38, and REA 1998 Table 40.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Exporter					2,276	226	109	6,172	784
Wholesale Distributor					21,444	29,181	14,377	9,193	9,804
Retail Distributor					8,336	829	3,222	2,555	2,272
Installer					18,762	25,302	18,429	24,917	20,491
End-User					689	657	994	66	63
Others					13	1,727	1,135	6,259	2,167
Total					51,520	57,922	38,266	49,162	35,581

Annual U.S. Geothermal Heat Pump Shipments by Export & Census Region (units)	*Source: EIA - Renewable Energy Annual 2001 Table 39, REA 2000 Table 37, REA 1999 Table 37, and REA 1998 Table 39.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Export					4,090	2,427	481	6,303	1,220
Midwest					11,874	13,402	12,240	13,112	10,749
Northeast					6,417	9,280	5,403	6,044	4,138
South					25,302	26,788	16,195	20,935	17,403
West					3,837	6,025	3,947	2,768	2,071
Total					51,520	57,922	38,266	49,162	35,581

Annual Geothermal Energy Consumption for Electric Generation (Trillion Btu)	*Source: EIA, Annual Energy Review 2001, Table 2.2b.*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S. Total	110	198	315	280	300	309	311	312	296

Technology Performance

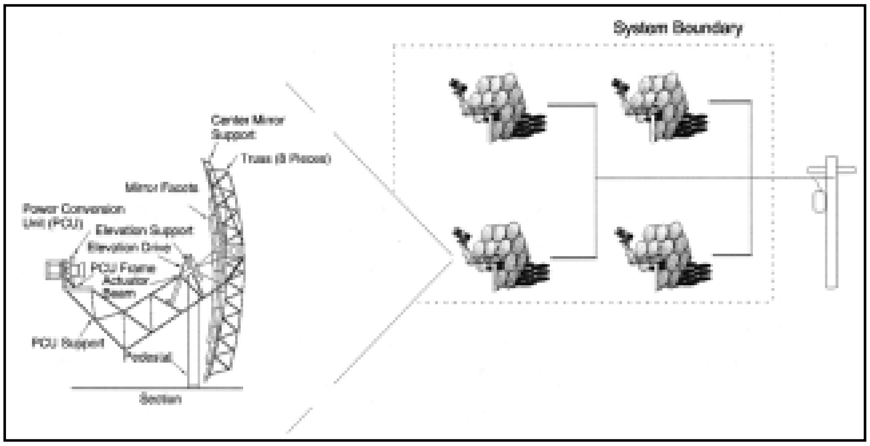
Efficiency	Source: Renewable Energy Technology Characterizations, EPRI TR-109496, 1997 (this document is currently being updated by DOE and the values most likely will change).								
		1980	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capacity Factor (%)	Flashed Steam			89	92	93	95	96	96
	Binary			89	92	93	95	96	96
	Hot Dry Rock			80	81	82	83	84	85
Cost									
		1980	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capital Cost ($/kW)	Flashed Steam			1,444	1,372	1,250	1,194	1,147	1,100
	Binary			2,112	1,994	1,875	1,754	1,696	1,637
	Hot Dry Rock			5,519	5,176	4,756	4,312	3,794	3,276
Fixed O&M ($/kW-yr)	Flashed Steam			96.4	87.1	74.8	66.3	62.25	58.2
	Binary			87.4	78.5	66.8	59.5	55.95	52.4
	Hot Dry Rock			219	207	191	179	171	163

Concentrating Solar Power

Technology Description

Concentrating Solar Power (CSP) systems concentrate solar energy 50 to 5,000 times to produce high-temperature thermal energy, which is used to produce electricity for distributed- or bulk-generation power applications.

System Concepts



- In CSP systems, highly reflective sun-tracking mirrors produce temperatures of 400ºC to 800ºC in the working fluid of a receiver; this heat is used in conventional heat engines (steam or gas turbines or Stirling engines) to produce electricity at system solar-to-electric efficiencies of up to 30%. Systems using advanced photovoltaics (PV) cells may achieve efficiencies greater than 35%.

Representative Technologies

- A parabolic trough system focuses solar energy on a linear oil-filled receiver, which collects heat to generate steam and power a steam turbine. When the sun is not shining, steam can be generated with fossil fuel to meet utility needs. Plant sizes can range from 10 MWe to 100 MWe.
- A power tower system uses many large heliostats to focus the solar energy onto a tower-mounted central receiver filled with a molten-salt working fluid that produces steam. The hot salt can be stored efficiently to allow power production to match utility demand even when the sun is not shining. Plant size can range from 30 MWe to 200 MWe.
- A dish/engine system (see diagram above) uses a dish-shaped reflector to power a small Stirling or Brayton engine/generator or a high-concentrator PV module mounted at the focus of the dish. Dishes are 2 to 25 kW in size, can be used individually or in small groups, and are easily hybridized with fossil fuel.

Technology Applications

- Concentrating solar power systems can be sized for village power (10 kilowatts) or grid-connected applications (up to 100 megawatts). Some systems use thermal storage during cloudy periods or at night. Others can be combined with natural gas such that the resulting hybrid power plants can provide higher-value, dispatchable power.

- To date, the primary use of CSP systems has been for bulk power supply to the southwestern grid. However, these systems were installed under very attractive power purchase rates that are not generally available today. With one of the best direct normal insolation resources anywhere on Earth, the southwestern states are still positioned to reap large and, as yet, largely uncaptured economic benefits from this important natural resource. California, Nevada, Arizona, and New Mexico are each exploring policies that will nurture the development of their solar-based industries.

• In addition to the concentrating solar power projects under way in this country, a number of projects are being developed in India, Egypt, Morocco, and Mexico. In addition, independent power producers are in the early stages of design and development for potential parabolic trough and/or power tower projects in Greece (Crete) and Spain. Given successful deployment of systems in one or more of these initial markets, several domestic project opportunities are expected to follow.
• Distributed-systems deployment opportunities are emerging for dish-engine systems. Many states are adopting green power requirements in the form of "portfolio standards" and renewable energy mandates. While the potential markets in the United States are large, the size of developing worldwide markets is immense. The International Energy Agency projects an increased demand for electrical power worldwide more than doubling installed capacity. More than half of this is in developing countries and a large part is in areas with good solar resources, limited fossil fuel supplies, and no power distribution network. The potential payoff for dish/engine system developers is the opening of these immense global markets for the export of power generation systems.

Current Status

• CSP technology is generally still too expensive to compete in widespread domestic markets without significant subsidies. Consequently, RD&D goals are to reduce costs of CSP systems to 5¢/kWh to 8¢/kWh with moderate production levels within five years, and below 5c/kWh at high production levels in the long term.
• Nine parabolic trough plants, with a total rated capacity of 354 MWe, were installed in California between 1985 and 1991. Their continuing operation has demonstrated their ability to achieve commercial costs of about 12¢/kWh to 14¢/kWh.
• Solar Two, a 10-MWe pilot power tower with three hours of storage, also installed in California, provided technical information needed to scale up to a 30-100 MW commercial plant, the first of which is now being planned in Spain.
• A number of prototype dish/Stirling systems are currently operating in Nevada, Arizona, Colorado, and Spain. High levels of performance have been established; durability remains to be proven, although some systems have operated for more than 10,000 hours.
• The CSP industry includes 25 companies who design, sell, own, and/or operate energy systems and power plants based on the concentration of solar energy. CSP companies include energy utilities, independent power producers or project developers, equipment manufacturers, specialized development firms, and consultants. While some firms only offer CSP products, many offer related energy products and services. Four of the 25 are “Fortune 500 Companies.” Current companies include:

Duke Solar Energy, LLC	Stirling Energy Systems
Nexant (a Bechtel Technology & Consulting Company)	Science Applications International Corp.
The Boeing Company	STM Corporation
KJC Operating Company	WGAssociates
SunRay Corporation	Morse & Associates
Arizona Public Service Corporation	United Innovations Inc.
Spencer Management Associates	Reflective Energies
Kearney & Associates	Industrial Solar Technologies
Nagel Pump	Spectralab
Clever Fellows Innovative Consortium	Salt River Project
Array Technologies	Energy Laboratories Inc.
Concentrating Technologies	Amonix
Ed Tek Inc.	

Technology History

Organized, large-scale development of solar collectors began in the United States in the mid-1970s under the Energy Research and Development Administration (ERDA) and continued with the establishment of the U.S. Department of Energy (DOE) in 1978.

Troughs:

- Parabolic trough collectors capable of generating temperatures greater than 500ºC (932 F) were initially developed for industrial process heat (IPH) applications. Acurex, SunTec, and Solar Kinetics were the key parabolic trough manufacturers in the United States during this period.
- Parabolic trough development also was taking place in Europe and culminated with the construction of the IEA Small Solar Power Systems (SSPS) Project/Distributed Collector System in Tabernas, Spain, in 1981. This facility consisted of two parabolic trough solar fields – one using a single-axis tracking Acurex collector and one the double-axis tracking parabolic trough collectors developed by M.A.N. of Munich, Germany.
- In 1982, Luz International Limited (Luz) developed a parabolic trough collector for IPH applications that was based largely on the experience that had been gained by DOE/Sandia and the SSPS projects.
- Southern California Edison (SCE) signed a power purchase agreement with Luz for the Solar Electric Generating System (SEGS) I and II plants, which came online in 1985. Luz later signed a number of Standard Offer (SO) power purchase contracts under the Public Utility Regulatory Policies Act (PURPA), leading to the development of the SEGS III through SEGS IX projects. Initially, the plants were limited by PURPA to 30 MW in size; later this limit was raised to 80 MW. In 1991, Luz filed for bankruptcy when it was unable to secure construction financing for its 10th plant (SEGS X).
- The 354 MWe of SEGS trough systems are still being operated today. Experience gained through their operation will allow the next generation of trough technology to be installed and operated much more cost-effectively.

Power Towers:

- A number of experimental power tower systems and components have been field-tested around the world in the past 15 years, demonstrating the engineering feasibility and economic potential of the technology.
- Since the early 1980s, power towers have been fielded in Russia, Italy, Spain, Japan, and the United States.
- In early power towers, the thermal energy collected at the receiver was used to generate steam directly to drive a turbine generator.
- The U.S.-sponsored Solar Two was designed to demonstrate the dispatchability provided by molten-salt storage and to provide the experience necessary to lessen the perception of risk from these large systems.
- U.S. Industry is currently pursuing a subsidized power tower project opportunity in Spain. This project, dubbed "Solar Tres," represents a 4x scale-up of the Solar 2 design.

Dish/Engine Systems:

- Dish/engine technology is the oldest of the solar technologies, dating back to the 1800s when a number of companies demonstrated solar-powered steam Rankine and Stirling-based systems.
- Development of modern technology began in the late 1970s and early 1980s. This technology used directly illuminated, tubular solar receivers, a kinematic Stirling engine developed for automotive applications, and silver/glass mirror dishes. Systems, nominally rated at 25 kWe, achieved solar-to-electric conversion efficiencies of around 30 percent. Eight prototype systems were deployed and operated on a daily basis from 1986 through 1988.
- In the early 1990s, Cummins Engine Company attempted to commercialize dish/Stirling systems

based on free-piston Stirling engine technology. Efforts included a 5 to 10 kWe dish/Stirling system for remote power applications, and a 25 kWe dish/engine system for utility applications. However, largely because of a corporate decision to focus on its core diesel-engine business, Cummins canceled their solar development in 1996. Technical difficulties with Cummins' free-piston Stirling engines were never resolved.

- Current dish/engine efforts are being continued by three U.S. industry teams - Science Applications International Corp. (SAIC) teamed with STM Corp., Boeing with Stirling Energy Systems, and WG Associates with Sunfire Corporation. SAIC and Boeing together have five 25kW systems under test and evaluation at utility, industry, and university sites in Arizona, California, and Nevada. WGA has two 10kW systems under test in New Mexico, with a third off-grid system being developed in 2002 on an Indian reservation for water-pumping applications.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for the three CSP configurations are projected to be:

	2000	2010	2020
Trough	9.5	5.4	4.4
Power Tower	9.5	4.8	3.6
Dish/Engine	17.9	6.1	5.5

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997 for Dish/Engine, and Program values for Trough and Power Tower.

- RD&D efforts are targeted to improve performance and lifetime, reduce manufacturing costs with improved designs, provide advanced designs for long-term competitiveness, and address barriers to market entry.
- Improved manufacturing technologies are needed to reduce the cost of key components, especially for first-plant applications where economies of scale are not yet available.
- Demonstration of Stirling engine performance and reliability in the field are critical to the success of dish/engine systems.
- DOE expects Dish/Stirling systems to be available by 2005, after deployment and testing of 1 MW (40 systems) during the next two years.
- Key DOE program activities are targeted to support the next commercial opportunities for these technologies, demonstrate improved performance and reliability of components and systems, reduce energy costs, and develop advanced systems and applications.
- The successful conclusion of Solar Two sparked worldwide interest in power towers. As Solar Two completed operations, an international consortium led by U.S. industry including Bechtel and Boeing (with technical support from Sandia National Laboratories), formed to pursue power tower plants worldwide, especially in Spain (where special solar premiums make the technology cost-effective), but also in Egypt, Morocco, and Italy. Their first commercial power tower plant is planned to be four times the size of Solar Two (about 40 MW equivalent, utilizing storage to power a 15MW turbine up to 24 hours per day).
- The World Bank's Solar Initiative is pursuing CSP technologies for less-developed countries. The World Bank considers CSP as a primary candidate for Global Environment Facility funding, which could total $1B to $2B for projects during the next two years.

Concentrating Solar Power

Market Data

U.S. Installations (electric only)

Source: Renewable Energy Project Information System (REPiS), Version 7, NREL, 2003, and Renewable Energy Technology Characterizations, EPRI TR-109496, 1997.

Cumulative Capacity (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.	0	24	274	354	364	364	364	364	354	354
Power Tower	0	10	0	0	10	10	10	10	0	0
Trough	0	14	274	354	354	354	354	354	354	354
Dish/Engine	0	0	0	0	0	0	0.125	0.125	0.125	0.125

Annual Generation from Cumulative Installed Capacity (Billion kWh)

Source: EIA, Annual Energy Outlook 1998-2003 Table A17, Renewable Resources in the Electric Supply, 1993 Table 4.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.			0.63	0.82	0.90	0.89	0.89	0.87	0.49	0.49

Annual U.S. Solar Thermal Shipments (Thousand Square Feet)

Source: EIA - Annual Energy Review 2001 Table 10.3 and Renewable Energy Annual 2001 Table 11.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Total[1]	19,398	NA	11,409	7,666	7,616	8,138	7,756	8,583	8,354	11,189
Imports	235	NA	1,562	2,037	1,930	2,102	2,206	2,352	2,201	3,502
Exports	1,115	NA	245	530	454	379	360	537	496	840

[1] Total shipments as reported by respondents include all domestic and export shipments and may include imports that subsequently were shipped to domestic or to foreign customers.

No data are available for 1985.

Technology Performance

Efficiency

Source: *Renewable Energy Technology Characterizations, EPRI TR-109496, 1997 (this document is currently being updated by DOE, and the values most likely will change), and TC revisions made by Hank Price of NREL for Trough technologies and Scott Jones of Sandia National Laboratory for Power Towers in 2001.*

		1980	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capacity Factor (%)	Power Tower			20.0	43.0	44.0	65.0	71.0	77.0
	Trough			34.0	33.3	41.7	51.2	51.2	51.2
	Dish			12.4	50.0	50.0	50.0	50.0	50.0
Solar to Electric Eff. (%)	Power Tower			8.5	15.0	16.2	17.0	18.5	20.0
	Trough			10.7	13.1	13.9	14.8	14.8	15.6
	Dish/Engine								

Cost*		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Total ($/kWp)	Power Tower				1,747	1,294	965	918	871
	Trough			4,033	2,103	1,633	1,277	1,185	1,072
	Dish/Engine			12,576	5,191	2,831	1,365	1,281	1,197
Total ($/kWnameplate)	Power Tower				3,145	2,329	2,605	2,475	2,345
	Trough			4,033	3,154	2,988	2,766	2,568	2,323
	Dish/Engine			12,576	5,691	3,231	1,690	1,579	1,467
O&M ($/kWh)	Power Tower			0.171	0.018	0.006	0.005	0.004	0.004
	Trough			0.025	0.017	0.013	0.009	0.007	0.007
	Dish/Engine			0.210	0.037	0.023	0.011	0.011	0.011
Levelized Cost of Energy	Power Tower				0.101	0.066	0.051	0.044	0.038
($/kWh)	Trough			0.160	0.101	0.077	0.057	0.052	0.047
	Dish/Engine				0.179		0.061	0.058	0.055

* Cost data for trough and power tower technologies are from 2001 revisions (in 2001$). Dish/Engine data for $/kWp excludes costs of hybrid system and $/kWnameplate includes hybrid costs (in 1997$).

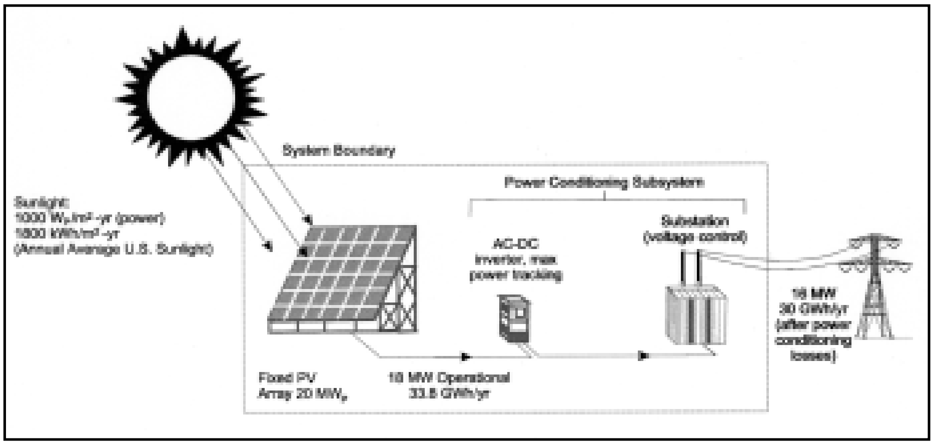
Photovoltaics

Technology Description

Photovoltaic (PV) arrays convert sunlight to electricity without moving parts and without producing fuel wastes, air pollution, or greenhouse gases (GHGs). Using solar PV for electricity and eventually transportation (from hydrogen production) will help reduce CO_2 worldwide.

System Concepts

- Flat-plate PV arrays use global sunlight; concentrators use direct sunlight. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground-mounted or on all types of buildings and structures (e.g., see semi-transparent solar canopy, right). PV dc output can be conditioned into grid-quality ac electricity, or dc can be used to charge batteries or to split water to produce H_2.



Representative Technologies

- Flat-plate cells are either constructed from crystalline silicon cells, or from thin films using amorphous silicon. Other materials such as copper indium diselinide (CIS) and cadmium telluride also hold promise as thin-film materials. The vast majority of systems installed today are in flat-plate configurations where multiple cells are mounted together to form a module. These systems are generally fixed in a single position, but can be mounted on structures that tilt toward the sun on a seasonal basis, or on structures that roll east to west over the course of the day.
- Photovoltaic concentrator systems use optical concentrators to focus direct sunlight onto solar cells for conversion to electricity. A complete concentrating system includes concentrator modules, support and tracking structures, a power-processing center, and land. PV concentrator module components include solar cells, an electrically isolating and thermally conducting housing for mounting and interconnecting the cells, and optical concentrators. The solar cells in today's concentrators are predominantly silicon, although gallium arsenide-based (GaAs) solar cells may be used in the future because of their high-conversion efficiencies. The housing places the solar cells at the focus of the optical concentrator elements and provides means for dissipating excess heat generated in the solar cells. The optical concentrators are generally Fresnel lenses but also can be reflectors.

Technology Applications

- PV systems can be installed as either grid supply technologies or as customer-sited alternatives to retail electricity. As suppliers of bulk grid power, PV modules would typically be installed in large array fields ranging in total peak output from a few megawatts on up. Very few of these systems have been installed to-date. A greater focus of the recent marketplace is on customer-sited systems, which may be installed to meet a variety of customer needs. These installations may be residential-size systems of just one kilowatt, or commercial-size systems of several hundred kilowatts. In either case, PV systems meet customer needs for alternatives to purchased power, reliable power, protection from price escalation, desire for green power, etc. Interest is growing in the use of PV systems as part of the building structure or façade ("building integrated"). Such systems use PV modules designed to look like shingles, windows, or other common building elements.

- PV systems are expected to be used in the United States for residential and commercial buildings; distributed utility systems for grid support; peak power shaving, and intermediate daytime load following; with electric storage and improved transmission, for dispatchable electricity; and H_2 production for portable fuel.
- Other applications for PV systems include electricity for remote locations, especially for billions of people worldwide who do not have electricity. Typically, these applications will be in hybrid minigrid or battery-charging configurations.
- Almost all locations in the United States and worldwide have enough sunlight for PV (e.g., U.S. sunlight varies by only about 25% from an average in Kansas).
- Land area is not a problem for PV. Not only can PV be more easily sited in a distributed fashion than almost all alternatives (e.g., on roofs or above parking lots), a PV-generating station 140 km-by-140 km sited at an average solar location in the United States could generate all of the electricity needed in the country (2.5×10^6 GWh/year), assuming a system efficiency of 10% and an area packing factor of 50% (to avoid self-shading). This area (0.3% of U.S.) is less than one-third of the area used for military purposes in the United States.

Current Status

- The cost of PV-generated electricity has dropped 15- to 20-fold; and grid-connected PV systems currently sell for about \$5–\$10/W_p (20 to 50¢/kWh), including support structures, power conditioning, and land. They are highly reliable and last 20 years or longer.
- Crystalline silicon is widely used and the most commercially mature photovoltaic material. Thin-film PV modules currently in production include three based on amorphous silicon, cadmium telluride, and CIS alloys.
- About 288 MW of PV were sold in 2000 (more than \$2 billion worth); total installed PV is more than 1 GW. The U.S. world market share is about 26%. Annual market growth for PV has been about 25% as a result of reduced prices and successful global marketing. In recent years, sales growth has accelerated to almost 40% per year. Hundreds of applications are cost-effective for off-grid needs. Almost two-thirds of U.S.-manufactured PV is exported. However, the fastest growing segment of the market is grid-connected PV, such as roof-mounted arrays on homes and commercial buildings in the United States. California is subsidizing PV systems because it is considered cost-effective to reduce their dependence on natural gas, especially for peak daytime loads for air-conditioning, which matches PV output.
- Highest efficiency for wafers of single-crystal or polycrystalline silicon is 24%, and for commercial modules is 13%–15%. Silicon modules currently cost about \$2-\$3/W_p to manufacture.
- During the past two years, *world record* solar cell sunlight-to-electricity conversion efficiencies were set by federally funded universities, national laboratories, or industry in copper indium gallium diselenide (19% cells and 12% modules) and cadmium telluride (16% cells, 11% modules). Cell and module efficiencies for these technologies have increased more than 50% in the past decade. Efficiencies for commercial thin-film modules are 5%–11%. A new generation of thin-film PV modules is going through the high-risk transition to first-time and large-scale manufacturing. If successful, market share could increase rapidly.
- Highest efficiencies for single-crystal Si and multijunction gallium arsenide (GaAs)-alloy cells for concentrators are 25%–34%; and for commercial modules are 15%–17%. Prototype systems are being tested in the U.S. desert SW.
- Current leading PV companies in 2000 and associated production of cells/modules are listed below:

Top PV Producers (2002)	U.S. Production	World Production
	MW	MW
Sharp	-	123.1
BP/Amoco Solarex	31	77.5
Kyocera	-	60
Shell Solar	46.5	55.5
Sanyo	-	35
AstroPower	29.7	29.7
RWE (ASE GMBH)	5	29.5
Isofoton	-	27.4
Mitsubishi	-	24
Photowatt	-	17
USSC	4	-
Evergreen Solar	1.9	-
Solec Intl	0.0	-
Other*	2.5	-
Total	120.6	478.6
World Total	-	560.3

Source: PV News, Vol. 22, No. 5, Page 2

Technology History

- French physicist Edmond Becquerel first described the photovoltaic (PV) effect in 1839, but it remained a curiosity of science for the next three quarters of a century. At only 19, Becquerel found that certain materials would produce small amounts of electric current when exposed to light. The effect was first studied in solids, such as selenium, by Heinrich Hertz in the 1870s. Soon afterward, selenium PV cells were converting light to electricity at more than 1 percent efficiency. As a result, selenium was quickly adopted in the emerging field of photography for use in light-measuring devices.
- Major steps toward commercializing PV were taken in the 1940s and early 1950s, when the Czochralski process was developed for producing highly pure crystalline silicon. In 1954, scientists at Bell Laboratories depended on the Czochralski process to develop the first crystalline silicon photovoltaic cell, which had an efficiency of 4 percent. Although a few attempts were made in the 1950s to use silicon cells in commercial products, it was the new space program that gave the technology its first major application. In 1958, the U.S. Vanguard space satellite carried a small array of PV cells to power its radio. The cells worked so well that PV technology has been part of the space program ever since.
- Even today, PV plays an important role in space, supplying nearly all power for satellites. The commercial integrated circuit technology also contributed to the development of PV cells. Transistors and PV cells are made from similar materials and operate on similar physical mechanisms. As a result, advances in transistor research provided a steady flow of new information about PV cell technology. (Today, however, this technology transfer process often works in reverse, as advances in PV research and development are sometimes adopted by the integrated circuit industry.)
- Despite these advances, PV devices in 1970 were still too expensive for most "down-to-Earth" uses. But, in the mid-1970s, rising energy costs, sparked by a world oil crisis, renewed interest in making PV technology more affordable. Since then, the federal government, industry, and research organizations have invested billions of dollars in research, development, and production. A thriving industry now exists to meet the rapidly growing demand for photovoltaic products.

Technology Future

The levelized cost of electricity (in constant 1997$/kWh) for PV are projected to be:

	2000	2010	2020
Utility-owned Residential (crystalline Si)	29.7	17.0	10.2
Utility-Scale Thin-Film	29.0	8.1	6.2
Concentrator	24.4	9.4	6.5

Source: *Renewable Energy Technology Characterizations*, EPRI TR-109496, 1997.
(Note that this document is currently being updated by DOE, and the values most likely will change).

- Crystalline Silicon - Most PV systems installed to-date have used crystalline silicon cells. That technology is relatively mature. In the future, cost-effectiveness will be achieved through incremental efficiency improvements, enhanced yields, and advanced lower-cost manufacturing techniques.
- Even though some thin-film modules are now commercially available, their real commercial impact is only expected to become significant during the next three to 10 years. Beyond that, their general use should occur in the 2005-2015 time frame, depending on investment levels for technology development and manufacture.
- Thin films using amorphous silicon, which are a growing segment of the U.S. market, have several advantages over crystalline silicon. It can be manufactured at lower cost, is more responsive to indoor light, and can be manufactured on flexible or low-cost substrates. Improved semiconductor deposition rates will reduce manufacturing costs in the future. Other thin-film materials will become increasingly important in the future. In fact, the first commercial modules using indium gallium diselinide thin-film devices were produced in 2000. Improved manufacturing techniques and deposition processes will reduce costs and help improve efficiency.
- Substantial commercial interest exists in scaling-up production of thin films. As thin films are produced in larger quantity, and as they achieve expected performance gains, they will become more economical for the whole range of applications.
- Multijunction cells with efficiencies of 38% at very high concentrations are being developed.
- Manufacturing research and supporting technology development hold important keys to future cost reductions. Large-scale manufacturing processes will allow major cost reductions in cells and modules. Advanced power electronics and non-islanding inverters will lessen barriers to customer adoption and utility interface.
- A unique multijunction GaAs-alloy cell developed at NREL was spun off to the space power industry, leading to a record cell (34%) and a shared R&D100 Award for NREL/Spectrolab in 2001. This device configuration is expected to dominate future space power for commercial and military satellites.

Photovoltaics

Market Data

PV Cell/Module Production (Shipments) *Source: PV News, Vol. 15, No. 2, Feb. 1996; Vol. 16, No. 2, Feb. 1997; Vol. 20, No. 2, Feb. 2001, and Volume 22, No. 5, May 2003 [Paul Maycock, www.pvenergy.com]*

Annual (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
U.S.	3	8	15	35	39	51	54	61	75	100	121
Japan	1	10	17	16	21	35	49	80	129	171	251
Europe	0	3	10	20	19	30	34	40	61	87	135
Rest of World	0	1	5	6	10	9	19	21	23	33	54
World Total	4	23	47	78	89	126	155	201	288	391	560
Cumulative (MW)	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
U.S.	5	45	101	219	258	309	363	424	499	599	720
Japan	1	26	95	185	206	241	290	370	499	670	921
Europe	1	13	47	136	155	185	219	259	320	407	542
Rest of World	0	3	20	45	55	65	83	104	127	160	214
World Total	7	87	263	585	674	800	954	1,156	1,444	1,835	2,395
U.S. % of World Sales	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Annual	71%	34%	32%	44%	44%	41%	35%	30%	26%	26%	22%
Cumulative	75%	52%	39%	37%	38%	39%	38%	37%	35%	33%	30%

Annual Capacity (Shipments retained, MW)* *Source: Strategies Unlimited*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.	1.4	4.2	5.1	8.4	9.2	10.5	13.6	18.4	21.3
Total World	3	15	39	68	79	110	131	170	246

*Excludes indoor consumer (watches/calculators).

Cumulative Capacity (Shipments retained, MW)*	*Source: Strategies Unlimited*								
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
U.S.	3	23	43	76	85	96	109	128	149
Total World	6	61	199	474	552	663	794	964	1,210

*Excludes indoor consumer (watches/calculators).

U.S. Shipments (MW)	*Source: EIA, Annual Energy Review, 2001, Table 10.5, and Renewable Energy Annual 2001, Table 26.*									
Annual Shipments	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Total		5.8	13.8	31.1	35.5	46.4	50.6	76.8	88.2	97.7
Imports		0.3	1.4	1.3	1.9	1.9	1.9	4.8	8.8	10.2
Exports	N/A	1.7	7.5	19.9	22.4	33.8	35.5	55.6	68.4	61.4
Domestic Total On-Grid*		0.4	0.2	1.7	1.8	2.2	4.2	6.9	4.9	
Domestic Total Off-Grid*		3.7	6.1	9.5	11.2	10.3	10.8	14.4	15.0	
Cumulative Shipments	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Total		35.2	84.7	193.3	228.8	275.2	325.7	402.5	490.7	588.4
Imports		1.0	5.6	14.3	16.2	18.0	19.9	24.7	33.5	43.7
Exports	N/A	5.7	32.9	104.0	126.5	160.3	195.8	251.3	319.7	381.0
Domestic Total On-Grid*		2.9	4.7	8.2	9.9	12.2	16.4	23.3	28.2	
Domestic Total Off-Grid*		26.6	47.2	81.1	92.4	102.7	113.5	127.9	142.9	

* Domestic Totals include imports and exclude exports.

Annual U.S. Installations (MW)	*Source: The 2000 National Survey Report of Photovoltaic Power Applications in the United States, prepared by Paul D. Maycock and Ward Bower, April 30, 2001, prepared for the IEA, Table E-1 and 2001 data from IEA Photovoltaic Power Systems Program http://www.oja-services.nl/iea-pvps/nsr01/usa.htm Table B.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Grid-Connected Distributed				1.5	2.0	2.0	2.2	3.7	5.5	12.0
Off-Grid Consumer				3.5	4.0	4.2	4.5	5.5	6.0	7.0
Government				0.8	1.2	1.5	1.5	2.5	2.5	1.0
Off-Grid Industrial/Commercial	N/A	N/A	N/A	4.0	4.4	4.8	5.2	6.5	7.5	9.0
Consumer (<20 w)				2.0	2.2	2.2	2.4	2.5	2.5	3.0
Central Station				0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total				11.8	13.8	14.7	15.8	20.7	24.0	32.0

Cumulative U.S. Installations* (MW)

Source: The 2000 National Survey Report of Photovoltaic Power Applications in the United States, prepared by Paul D. Maycock and Ward Bower, April 30, 2001, prepared for the IEA, Table 1 and 2001 data from IEA Photovoltaic Power Systems Program http://www.oja-services.nl/iea-pvps/nsr01/usa.htm Table 1.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Off-grid Residential				19.3	23.3	27.5	32.0	37.5	43.5	50.5
Off-grid Nonresidential				25.8	30.2	35.0	40.2	46.7	55.2	64.7
On-grid Distributed	N/A	N/A	N/A	9.7	11.0	13.7	15.9	21.1	28.1	40.6
On-grid Centralized				12.0	12.0	12.0	12.0	12.0	12.0	12.0
Total				66.8	76.5	88.2	100.1	117.3	138.8	167.8

* Excludes installations less than 40kW.

Annual World Installations (MW)

Source: PV News, Vol. 19, No.11, Nov. 2000

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Consumer Products			16		22	26	30	35	40
U.S. Off-Grid Residential			3		8	9	10	13	16
World Off-Grid Rural			6		15	19	24	31	35
Communications/ Signal	N/A	N/A	14	N/A	23	28	31	35	42
PV/Diesel, Commercial			7		12	16	20	25	30
Grid-Conn Res., Commercial			1		7	27	35	60	85
Central Station (>100kW)			1		2	2	2	2	2
Total			48		89	127	152	201	250

Annual U.S. Shipments by Cell Type (MW)

Source: PV News, Vol. 15, No. 2, Feb. 1996; Vol. 16, No. 2, Feb. 1997; Vol. 17, No. 2, Feb. 1998; Vol. 18, No. 2, Feb. 1999; Vol. 19, No. 3, March 2000; and Vol. 20, No. 3, March 2001 and Vol. 22, No. 5, May 2003.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Single Crystal				22.0	24.1	31.8	30.0	36.6	44.0	63.0
Flat-Plate Polycrystal (other than ribbon)				9.0	10.3	14.0	14.7	16.0	17.0	20.6
Amorphous Silicon				1.3	1.1	2.5	3.8	5.3	6.5	7.3
Crystal Silicon Concentrators				0.3	0.7	0.7	0.2	0.5	0.5	0.5
Ribbon Silicon	N/A	N/A	N/A	2.0	3.0	4.0	4.0	4.2	5.0	6.9
Cadmium Telluride				0.1	0.4	0	0	0	0	0.6
Microcrystal SI/Single SI										0
SI on Low-Cost-Sub				0.1	0.3	0.5	1.0	2.0	2.0	1.7
A-SI on Cz Slice									0	0
Total				34.8	39.9	53.5	53.7	64.6	75	100.6

Annual World Shipments by Cell Type (MW) *Source: PV News, Vol. 15, No. 2, Feb. 1996; Vol. 16, No. 2, Feb. 1997; Vol. 17, No. 2, Feb. 1998; Vol. 18, No. 2, Feb. 1999; Vol. 19, No. 3, March 2000;and Vol. 20, No. 3, March 2001 and Vol. 22, No. 5, May 2003.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Single Crystal				46.7	48.5	62.8	59.8	73.0	89.7	150.41
Flat-Plate Polycrystal				20.1	24.0	43.0	66.3	88.4	140.6	278.9
Amorphous Silicon				9.1	11.7	15.0	19.2	23.9	27.0	28.01
Crystal Silicon Concentrators				0.3	0.7	0.2	0.2	0.5	0.5	0.5
Ribbon Silicon	N/A	N/A	N/A	2.0	3.0	4.0	4.0	4.2	14.7	16.9
Cadmium Telluride				1.3	1.6	1.2	1.2	1.2	1.2	2.1
Microcrystal SI/Single SI										3.7
SI on Low-Cost-Sub				0.1	0.3	0.5	1.0	2.0	2.0	1.7
A-SI on Cz Slice								8.1	12.0	30
Total				79.5	89.8	126.7	151.7	201.3	287.7	512.22

Annual U.S. Shipments by Cell Type (MW) *Source: EIA, Renewable Energy Annual 1997, Table 27, REA 2000 Table 26, REA 2001, Table 28, and Solar Collector Manufacturing Activity annual reports, 1982-1992.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Single-Crystal Silicon				19.9	21.7	30.0	30.8	47.2	51.9	54.7
Cast and Ribbon Crystalline Silicon				9.9	12.3	14.3	16.4	26.2	33.2	29.9
Crystalline Silicon Total		5.5	12.5	29.8	34.0	44.3	47.2	73.5	85.2	84.6
Thin-Film Silicon	N/A	0.3	1.3	1.3	1.4	1.9	3.3	3.3	2.7	12.5
Concentrator Silicon				0.1	0.2	0.2	0.1	0.1	0.3	0.5
Other										
Total		5.8	13.8	31.2	35.6	46.3	50.6	76.8	88.2	97.7

Annual Grid-Connected Capacity (MW) *Source: The 2000 National Survey Report of Photovoltaic Power Applications in the United States, prepared by Paul D. Maycock and Ward Bower, April 30, 2001, for the IEA, derived from Table 1 and 2001 data from IEA Photovoltaic Power Systems Program http://www.oja-services.nl/iea-pvps/nsr01/usa2.htm derived from Table 1; Japan data from PV News, Vol. 20, No. 7, July 2001.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.	N/A	N/A	N/A		1.3	2.7	2.2	5.2	7.0	12.5
Japan				3.9	7.5	19.5	24.1	57.7	95.8	

Cumulative Grid-Connected Capacity (MW)	*Source: The 2000 National Survey Report of Photovoltaic Power Applications in the United States, prepared by Paul D. Maycock and Ward Bower, April 30, 2001, for the IEA, Table 1 and 2001 data from IEA Photovoltaic Power Systems Program http://www.oja-services.nl/iea-pvps/nsr01/usa2.htm Table 1; Japan data from PV News, Vol. 20, No. 7, July 2001.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.	N/A	N/A	N/A	21.7	23.0	25.7	27.9	33.1	40.1	52.6
Japan				5.80	13.3	32.8	56.9	115	210	

Japan Grid-Connected Capacity (MW)	*Source: IEA Photovoltaic Power Systems Program http://www.oja-services.nl/iea-pvps/nsr01/jpn2.htm Table 1.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Annual				6.0	9.7	22.6	34.7	71.3	114.8	116.0
Cumulative				13.7	23.4	46.0	80.7	151.9	266.7	382.7

Annual U.S.-Installed Capacity (MW)	Source: *Renewable Electric Plant Information System (REPiS), Version 7, NREL, 2003.*										
Top 10 States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
California		0.034	0.016	0.720	0.900	0.606	0.577	2.993	5.833	7.007	15.693
Arizona		0.004		0.026	0.067	0.732	0.296	0.578	0.635	1.325	2.683
New York			0.013	0.067	0.344	0.021	0.346	0.041	0.377		1.078
Hawaii				0.013	0.031	0.008	0.291	0.113	0.250	0.225	
Texas	0.006	0.015	0.002	0.008		0.010	0.112	0.144	0.120		
Colorado				0.018	0.100	0.006	0.132	0.344	0.137		
Ohio						0.001	0.001	0.010	0.237	0.008	0.388
Florida	0.009		0.008	0.018		0.036	0.058	0.106	0.199	0.031	0.045
Georgia					0.352			0.019	0.221		
Illinois						0.002	0.005	0.034	0.043	0.449	
Total U.S.	0.015	0.078	0.049	1.042	2.035	1.678	1.984	5.040	8.807	9.221	20.174

Cumulative U.S.-Installed Capacity (MW)	Source: *Renewable Electric Plant Information System (REPiS), Version 7, NREL, 2003.*										
Top 10 States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
California	0.002	1.369	2.803	6.495	7.396	8.002	8.579	11.572	17.405	24.412	40.104
Arizona	0.008	0.032	0.048	0.097	0.164	0.896	1.192	1.771	2.406	3.731	6.414
New York	0.000	0.000	0.013	0.226	0.569	0.590	0.936	0.977	1.353	1.353	2.431
Hawaii	0.000	0.014	0.033	0.046	0.077	0.085	0.376	0.489	0.739	0.964	0.964
Texas	0.006	0.021	0.296	0.367	0.367	0.376	0.488	0.633	0.753	0.781	0.781
Colorado	0.000	0.000	0.010	0.040	0.140	0.146	0.278	0.622	0.759	0.759	0.759
Ohio	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.012	0.249	0.257	0.644
Florida	0.009	0.093	0.117	0.135	0.135	0.171	0.229	0.336	0.535	0.566	0.612
Georgia	0.000	0.000	0.000	0.000	0.352	0.352	0.352	0.371	0.592	0.592	0.592
Illinois	0.000	0.000	0.021	0.021	0.021	0.023	0.029	0.062	0.105	0.553	0.553
Total U.S. [1]	0.025	2.104	4.100	8.503	10.539	12.217	14.201	19.241	28.048	37.268	57.442

[1] There are an additional 2.0 MW of photovoltaic capacity that are not accounted for here because they have no specific online date.

Technology Performance

Source: *Renewable Energy Technology Characterizations, EPRI TR-109496, 1997.*
(Note that this document is currently being updated by DOE, and the values most likely will change).

Efficiency		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Cell (%)	Crystalline Silicon			24	24.7				
	Thin Film			18.0	19.0	20.0	21.0	21.5	22.0
	Concentrator			20.0	23.0	26.0	33.0	35.0	37.0
Module (%)	Crystalline Silicon			14.0	16.0	17.0	18.0	18.5	19.0
	Thin Film	N/A	N/A	10.0	12.0	15.0	17.0	17.5	18.0
	Concentrator								
System (%)	Crystalline Silicon			11.3	13.1	14.1	15.1	15.6	16.1
	Thin Film			4.8	7.2	8.8	11.2	12.0	12.8
	Concentrator			13.8	15.1	17.1	21.7	23.0	24.3
Cost		**1980**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Module ($/Wp)	Crystalline Silicon			3.8	3.0	2.3	1.8	1.4	1.1

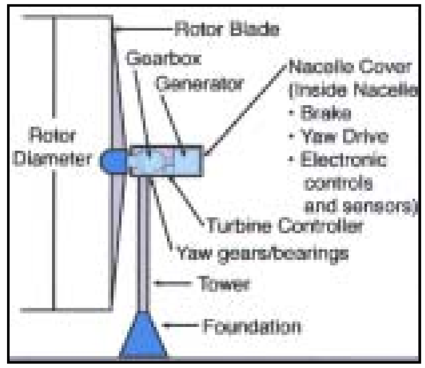
	Thin Film			3.8	2.2	1.0	0.5	0.4	0.4
	Concentrator			1.8	1.5	0.7	0.6	0.5	0.5
BOS ($/Wp)	Crystalline Silicon			2.7	2.1	1.6	1.2	0.9	0.7
	Thin Film			3.7	2.1	1.3	0.7	0.6	0.5
	Concentrator	N/A	N/A	3.6	2.7	1.2	1.0	0.8	0.7
Total ($/Wp)	Crystalline Silicon *			6.5	5.1	3.9	3.0	2.4	1.8
	Thin Film			7.5	4.3	2.3	1.2	1.1	0.9
	Concentrator			7.6	4.0	2.0	1.6	1.3	1.1
O&M ($/kWh)	Crystalline Silicon			0.008	0.007	0.006	0.006	0.006	0.005
	Thin Film			0.023	0.008	0.003	0.002	0.002	0.001
	Concentrator			0.047	0.020	0.010	0.008	0.007	0.006

* Range in total capital cost for crystalline silicon in 2000 is $5.1/Wp to $9.1/Wp depending on market supply and demand. (Source: John Mortensen, Factors Associated with Photovoltaic System Costs, June 2001, NREL/TP 620.29649, Page 3).

Wind Energy

Technology Description

Wind-turbine technology converts the kinetic energy in the wind to mechanical energy and ultimately to electricity. Grid-connected wind power reduces GHG emissions by displacing the need for natural gas- and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially overseas.



System Concepts

- The principle of wind energy conversion is simple: Wind passing over the blade creates lift, producing a torque on the rotor shaft that turns a gearbox. The gearbox is coupled to an electric generator that produces power at the frequency of the host power system. Some new innovative designs use low-speed generators, which eliminate the need for a gearbox.

Representative Technologies

- Two major design approaches are being used: (1) typical of historic European technology—three-bladed, up-wind, stiff, heavy machines that resist cyclic and extreme loads, and (2) lightweight, flexible machines that bend and absorb loads, primarily being developed by U.S. designers. Several alternative configurations within each approach are being pursued.

Technology Applications

- Thirty-seven states have land area with good winds (13 mph annual average at 10 m height, wind Class 4, or better).
- For wind-farm or wholesale power applications, the principal competition is natural gas for new construction and natural gas in existing units for fuel saving. Utility restructuring is a critical challenge to increased deployment in the near-term because it emphasizes short-term, low capital-cost alternatives and lacks public policy to support deployment of sustainable technologies such as wind energy.

Current Status

- Wind technology is competitive today in bulk power markets with support from the production tax credit, and in high-value niche applications or markets that recognize noncost attributes.
- Current performance is characterized by levelized costs of 4 to 5.5¢/kWh (depending on resource intensity and financing structure), capacity factors of 30 to 40 percent, availability of 95 to 98%, total installed project costs ("overnight" – not including construction financing) of $800 to $1,100/kW, and efficiencies of 65% to 75% of the theoretical (Betz limit) maximum.
- The worldwide annual market growth rate for wind technology is at a level of 30% with new markets opening in many developing countries. Domestic public interest in environmentally responsible electric generation technology is reflected by new state energy policies and in the success of "green marketing" of wind power across the country.
- Preliminary estimates are that installed capacity at the end of 2001 was 4,260 MW in the United States, and 23,300 MW worldwide; compared to 2,550 MW in the United States and 17,653 worldwide in 2000; and 2,450 MW in the United States and 13,598 MW worldwide in 1999.
- U.S. energy generation from wind was nearly 5 TWh out of a worldwide total of 30 TWh in 2000, up from 4.5 TWh out of an approximate total of 26 TWh in 1999.
- Twelve states had more than 20 MW of large wind-turbine capacity at the end of 2001, with 15 additional states having less than 20 MW each.
- In the United States, the wind industry is thinly capitalized, except for the acquisition of Enron

Wind Corporation by General Electric Co. About six manufacturers and six to 10 developers characterize the U.S. industry.

- Enron Wind Corporation has been acquired by General Electric Corporation, Power Turbine Division.
- In Europe, there are about 12 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively participating in the U.S. market.
- Current leading wind companies and sales volume are shown below:

	U.S. Market (2002)		World Market (2002)	
	MW	Percent	MW	Percent
Vestas (DK)	172	40.2	1,605	22.2
NEG Micon (DK)	119	27.8	1,033	14.3
GE Wind (USA)	61	14.3	1,334	18.5
Bonus (DK)	48	11.2	509	7.0
Mitsubishi (JP)	25	5.9	30	0.4
Nordex (DK)	2.6	0.6	504	7.0
Enercon (D)	-	-	617	13.7
Gamesa (ESP)	-	-	854	11.8
Ecotecnia (ESP)	-	-	120	1.7
Repower (D)	-	-	223	3.1
MADE (ESP)	-	-	247	3.4
Ecotecnia (ESP)	-	-	120	1.7
Others	-	-	371	5.1

Sources: U.S. Market: NREL estimate based on BTM Consult, ApS, "World Market Update 2003", World Market: BTM Consult, ApS, "World Market Update 2003"

Technology History

- Prior to 1980, DOE sponsored, and NASA managed, large-scale turbine development – starting with hundred-kilowatt machines and culminating in the late 1980s with the 3.2-MW, DOE-supported Mod-5 machine built by Boeing.
- Small-scale (2-20 kW) turbine development efforts also were supported by DOE at the Rocky Flats test site. Numerous designs were available commercially for residential and farm uses.
- In 1981, the first wind farms were installed in California by a small group of entrepreneurial companies. PURPA provide substantial regulatory support for this initial surge.
- During the next five years, the market boomed, installing U.S., Danish, and Dutch turbines.
- By 1985, annual market growth had peaked at 400 MW. Following that, federal tax credits were abruptly ended, and California incentives weakened the following year.
- In 1988, European market exceeded the U.S. for the first time, spurred by ambitious national programs. A number of new companies emerged in the U.K. and Germany.
- In 1989, DOE's focus changed to supporting industry-driven research on components and systems. At the same time, many U.S. companies became proficient in operating the 1600 MW of installed Capacity in California. They launched into value engineering and incremental increases in turbine size.
- DOE program supported value-engineering efforts and other advanced turbine-development efforts.
- In 1992, Congress passed the Renewable Energy Production Tax Credit (REPI), which provided a 1.5 cent/kWh tax credit for wind-produced electricity. Coupled with several state programs and mandates, installations in the United States began to increase.
- In 1997, Enron purchased Zond Energy Systems, one of the value-engineered turbine manufacturers. In 2002, General Electric Co. purchased Enron Wind Corporation.
- In FY2001, DOE initiated a low wind-speed turbine development program to broaden the U.S. cost-competitive resource base.

Technology Future

The levelized cost of electricity for wind energy technology is projected to be:

	2000	2002	2010	2020
Class 4	6.0	5.5	3.0	2.7
Class 6	4.2	4.0	2.4	2.2

Assumptions include: 30-year levelized cost, constant January 2002 dollars, generation company ownership/financial assumptions; wind plant comprised of 100 turbines; no financial incentives included.

Source: FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001

- Wind energy's competitiveness by 2005 will be affected by policies regarding ancillary services and transmission and distribution regulations. Substantial cost reductions are expected for wind turbines designed to operate economically in low wind-speed sites, which will increase the amount of economical wind resource areas by 20-fold, and will be within 100 miles of most load centers.
- Initial lower levels of wind deployment (up to 15–20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. Inasmuch as the wind blows only intermittently, intensive use of this technology at larger penetrations may require modification to system operations or ancillary services. Transmission infrastructure upgrades and expansion will be required for large penetrations of wind energy to service major load centers.
- Over the long-term, as more high wind sites become used, emphasis will shift toward installation in lower wind-speed sites. Advances in technology will include various combinations of the following improvements, accomplished through continuing R&D:

*Tower*s – taller for more energy, softer to shed loads, advanced materials, and erection techniques to save cost

Rotors – Improving airfoils and plan forms to increase energy capture. For instance, a variable rotor diameter; larger rotors at the same cost or small cost increase by optimizing design and manufacturing, using lighter materials, and implementing controls to mitigate loads.

Drive Train and Generators – New designs to reduce weight and cost. Advances in power electronics and operational algorithms to optimize drive-train efficiencies, especially by increasing low efficiencies in ranges of operation that are currently much lower than those in the peak range. In addition to new power electronics and operational approaches, possible advances include permanent magnet generators, and use of single-stage transmissions coupled with multiple smaller, simpler, off-the-shelf generators that can be purchased from high-volume manufacturers.

Controls – By reducing loads felt throughout the turbine, various approaches for passive and active control of turbines will enable larger, taller structures to be built for comparatively small cost increases, resulting in improvements in system cost of energy.

Design Codes – Reductions in design margins also will decrease the cost of turbines and allow for larger turbines to be built for comparatively small increases in cost, resulting in improvements in system cost of energy.

Foundations – New designs to lower cost.

Utility Grid Integration – Models and tools to analyze the steady and dynamic impact and operational characteristics of large wind farms on the electric grid will facilitate wind power integration. Improved wind forecasting and development of various enabling technologies will increase the value of wind power.

Wind

Market Data

Grid-Connected Wind Capacity (MW)	*Source: Reference IEA (data supplemented by Windpower Monthly, April 2001), 2001 data from Windpower Monthly, January 2002, 2002 data from AWEA "Global Wind Energy Market Report 2003".*										
Cumulative	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
U.S.	10	1,039	1,525	1,770	1,794	1,741	1,890	2,455	2,554	4,240	4,685
Denmark	3	50	310	630	785	1,100	1,400	1,752	2,338	2,417	2,880
Netherlands	0	0	49	255	305	325	364	416	447	483	688
Germany	2	3	60	1,137	1,576	2,082	2,874	4,445	6,095	8,100	12,001
Spain	0	0	9	126	216	421	834	1,539	2,334	3,175	4,830
UK	0	0	6	193	264	324	331	344	391	477	552
Europe	5	58	450	2,494	3,384	4,644	6,420	9,399	12,961	16,362	23,056
India	0	0	20	550	820	933	968	1,095	1,220	1,426	1,702
Japan	0	0	1	10	14	7	32	75	121	250	415
Rest of World	0	0	6	63	106	254	315	574	797	992	1,270
World Total	15	1,097	2,002	4,887	6,118	7,579	9,625	13,598	17,653	23,270	31,128

Installed U.S. Wind Capacity (MW)	*Source: Renewable Energy Project Information System (REPiS), Version 7, NREL, 2003.*										
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
Annual	0.02	337	154	43	1	8	188	657	185	1,410	678
Cumulative[1]	0.06	674	1,569	1,778	1,779	1,787	1,975	2,632	2,817	4,227	4,905

[1] There are an additional 204.9 MW of wind capacity that are not accounted for here because they have no specific online date.

Annual Market Shares

Source: US DOE- 1982-87 wind turbine shipment database; 1988-94 DOE Wind Program Data Sheets; 1996-2000 American Wind Energy Association

	1980	1985	1990	1995	1996	1997	1998	1999	2000
U.S. Mfg Share of U.S. Market	98%	44%	36%	67%	NA	38%	78%	44%	0%
U.S. Mfg Share of World Market	65%	42%	20%	5%	2%	4%	13%	9%	6%

State-Installed Capacity

Source: American Wind Energy Association. http://www.awea.org/projects/index.html

Annual State-Installed Capacity (MW)

Top 10 States	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002
California*		N/A	N/A	3.0	0	8.4	0.7	250.0	0	67.1	108
Texas		0	0	41.0	0	0	0	139.2	0	915.2	0
Iowa		0	0	0.1	0	1.2	3.1	237.5	0	81.8	98.5
Minnesota		0	0	0	0	0.2	109.2	137.6	17.8	28.6	16.8
Washington		0	0	0	0	0	0	0	0	178.2	50.0
Oregon		0	0	0	0	0	25.1	0	0	132.4	60.9
Wyoming		0	0	0	0.1	0	1.2	71.3	18.1	50.0	0
Kansas		0	0	0	0	0	0	1.5	0	112.2	0
West Virginia		0	0	0	0	0	0	0	0	0	66.0
Colorado		0	0	0	0	0	0	21.6	0	39.6	0
Total of 10 States		N/A	N/A	44	0	10	139	859	36	1,605	400
Total U.S.		N/A	N/A	44	1	16	142	884	67	1,694	410

Cumulative State-Installed Capacity (MW)

Top 10 States (as of 2001)	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002
California*		N/A	N/A	1,387	1,387	1,396	1,396	1,646	1,646	1,714	1,822
Texas		0	0	41.0	41.0	41.0	41.0	180.2	180.2	1,096	1095.5
Iowa		0	0	0.7	0.8	2.0	5.0	242.5	242.5	324.2	422.7
Minnesota		0	0	25.7	25.7	25.9	135.1	272.7	290.5	319.1	335.9
Washington		0	0	0	0	0	0	0	0	178.2	228.2
Oregon		0	0	0	0	0	25.1	25.1	25.1	157.5	218.4
Wyoming		0	0	0	0.1	0.1	1.3	72.5	90.6	140.6	140.6

Kansas		0	0	0	0	0	0	1.5	1.5	113.7	113.7
West Virginia		0	0	0	0	0	0	0	0	0	66.0
Colorado		0	0	0	0	0	0	21.6	21.6	61.2	61.2
Total of 10 States	N/A	N/A	1,454	1,455	1,465	1,604	2,462	2,498	4,104	4,504	1,822
Total U.S.	10	1,039	1,525	1,697	1,698	1,706	1,848	2,511	2,578	4,275	4,685

* The data set includes 1,193.53 MW of wind in California that is not given a specific installation year, but rather a range of years (1072.36 MW in 1981-1995, 87.98 in 1982-1987, and 33.19 MW in "mid-1980's"), this has led to the "Not Available" values for 1985 and 1990 for California and the totals, and this data is not listed in the annual installations, but has been added to the cumulative totals for 1995 and on.

Cumulative Installed Capacity (GW) — *Source: EIA, Annual Energy Review 2001 Table 8.7b*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.	NA	(s)	1.8	1.7	1.7	1.6	1.7	2.3	2.4	4.1

(s) – less than .05 GW

Annual Generation from Cumulative Installed Capacity (Billion kWh) — *Source: U.S. - EIA, Annual Energy Review 2001 Table 8.2b; IEA Countries – International Energy Agency Wind Energy Annual Reports, 1995-2001.*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.	NA	0.01	2.3	3.2	3.2	3.3	3.0	4.5	5.6	5.8
IEA Countries				7.1	8.4	10.9	11.3	22	26.4	37.2

Annual Wind Energy Consumption for Electric Generation (Trillion Btu) — *Source: U.S. - EIA, Annual Energy Review 2001 Table 2.2b*

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S.	NA	(s)	24	33	33	34	31	46	57	59

(s) – less than .5 Trillion Btu

Technology Performance

Energy Production			Source: *U.S.DOE Wind Program, 1980-1995, FY03 U.S.DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020*								
			1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
	Capacity Factor (%)	Class 4		10	15	20	25.2	32.6	44.7	46.5	47.1
		Class 6		20	22	25	39.4	44.3	49.6	50.9	53.8
	Specific Energy (kWh/m^2*)	Class 4		500	800	850	900	1,110	1,260	1,310	1,330
		Class 6		900	1,150	1,300	1,400	1,650	1,700	1,740	1,760
	Production Efficiency** (kWh/kW)	Class 4	200	650	1,300	1,750	2,200	2,860	3,500	3,600	3,600
		Class 6	800	1,700	1,900	2,200	3,450	3,880	4,350	4,450	4,700

* m^2 is the rotor swept area.

** Production Efficiency is the net energy per unit of installed capacity.

Cost*			Source: *FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001.*								
			1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
	Project Cost ($/kW)	Class 4					1,000	915	910	880	860
	(Overnight costs)	Class 6					1,000	900	800	770	750
	O&M ($/kW)	Class 4					11.0	7.9	7.0	6.9	6.6
		Class 6					17.3	8.0	7.8	7.6	7.5
	Fixed O&M & Land	Class 4					8.0	8.0	8.0	8.0	8.0
	($/kW)	Class 6					8.0	8.0	8.0	8.0	8.0

Specific Cost* (Project Capital Cost Per Rotor Captured Area - $/m2)		Source: *FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020.*								
		1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
	Class 4					382	357	293	283	277
	Class 6					414	340	312	300	276

* Jan. 2002 dollars

Levelized Cost of Energy* ($/kWh)

Source: *U.S. DOE Wind Program 1980-1985; FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020*

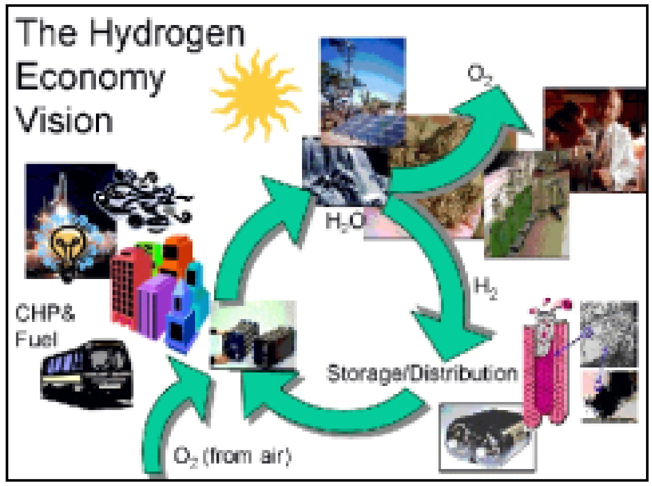
	1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Class 4			0.12	0.080	0.060	0.041	0.030	0.028	0.027
Class 6			0.08	0.060	0.042	0.027	0.024	0.023	0.022

* 30-year term, constant January 2002 dollars. Generation Company Ownership/Financial Assumptions. Wind plant comprised of 100 turbines. No financial incentives are included.

Hydrogen

Technology Description

Like electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Hydrogen and electricity can be converted from one to the other using electrolyzers (electricity to hydrogen) and fuel cells (hydrogen to electricity). Hydrogen is an effective energy storage medium, particularly for distributed generation. When hydrogen produced from renewable resources is used in fuel cell vehicles or power devices, there are very few emissions—the major byproduct is water. With improved conventional energy conversion and carbon-capture technologies, hydrogen from fossil resources can be used efficiently with few emissions.



The Hydrogen Economy vision is based on a clean and elegant cycle: separate water into hydrogen and oxygen using renewable or nuclear energy, or fossil resources with carbon sequestration. Use the hydrogen to power a fuel cell, internal combustion engine, or turbine, where hydrogen and oxygen (from air) recombine to produce electrical energy, heat, and water to complete the cycle. This process produces no particulates, no carbon dioxide, and no pollution.

System Concepts

- Hydrogen made via electrolysis from excess nuclear or renewable energy can be used as a sustainable transportation fuel or stored to meet peak-power demand. It also can be used as a feedstock in chemical processes.
- Hydrogen produced by decarbonization of fossil fuels followed by sequestration of the carbon can enable the continued, clean use of fossil fuels during the transition to a carbon-free Hydrogen Economy.
- A hydrogen system is comprised of production, storage, distribution, and use.
- A fuel cell works like a battery but does not run down or need recharging. It will produce electricity and heat as long as fuel (hydrogen) is supplied. A fuel cell consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around an electrolyte. Hydrogen is fed to the anode, and oxygen is fed to the cathode. Activated by a catalyst, hydrogen atoms separate into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat. Fuel cells can be used to power vehicles, or to provide electricity and heat to buildings.

Representative Technologies

Hydrogen production

- Thermochemical conversion of fossil fuels, biomass, and wastes to produce hydrogen and CO_2 with the CO_2 available for sequestration (large-scale steam methane reforming is widely commercialized)
- Renewable (wind, solar, geothermal, hydro) and nuclear electricity converted to hydrogen by electrolysis of water (commercially available electrolyzers supply a small but important part of the super-high-purity hydrogen market)
- Photoelectrochemical and photobiological processes for direct production of hydrogen from sunlight and water.

Hydrogen storage
- Pressurized gas and cryogenic liquid (commercial today)
- Higher pressure (10,000 psi), carbon-wrapped conformable gas cylinders
- Cryogenic gas
- Chemically bound as metal or chemical hydrides or physically adsorbed on carbon nanostructures

Hydrogen distribution
- By pipeline (relatively significant pipeline networks exist in industrial areas of the Gulf Coast region, and near Chicago)
- By decentralized or point-of-use production using natural gas or electricity
- By truck (liquid and compressed hydrogen delivery is practiced commercially)

Hydrogen use
- Transportation sector: internal combustion engines or fuel cells to power vehicles with electric power trains. Potential long-term use as an aviation fuel and in marine applications
- Industrial sector: ammonia production, reductant in metal production, hydrotreating of crude oils, hydrogenation of oils in the food industry, reducing agent in electronics industry, etc.
- Buildings sector: combined heat, power, and fuel applications using fuel cells
- Power sector: fuel cells, gas turbines, generators for distributed power generation

Technology Applications

- In the United States, nearly all of the hydrogen used as a chemical (i.e. for petroleum refining and upgrading, ammonia production) is produced from natural gas. The current main use of hydrogen as a fuel is by NASA to propel rockets.
- Hydrogen's potential use in fuel and energy applications includes powering vehicles, running turbines or fuel cells to produce electricity, and generating heat and electricity for buildings. The current focus is on hydrogen's use in fuel cells.

The primary fuel cell technologies under development are:

Phosphoric acid fuel cell (PAFC) - A phosphoric acid fuel cell (PAFC) consists of an anode and a cathode made of a finely dispersed platinum catalyst on carbon paper, and a silicon carbide matrix that holds the phosphoric acid electrolyte. This is the most commercially developed type of fuel cell and is being used in hotels, hospitals, and office buildings. The phosphoric acid fuel cell also can be used in large vehicles, such as buses.

Proton-exchange membrane (PEM) - The proton-exchange membrane (PEM) fuel cell uses a fluorocarbon ion exchange with a polymeric membrane as the electrolyte. The PEM cell appears to be more adaptable to automobile use than the PAFC type of cell. These cells operate at relatively low temperatures and can vary their output to meet shifting power demands. These cells are the best candidates for light-duty vehicles, for buildings, and much smaller applications.

Solid oxide fuel cells (SOFC) - Solid oxide fuel cells (SOFC) currently under development use a thin layer of zirconium oxide as a solid ceramic electrolyte, and include a lanthanum manganate cathode and a nickel-zirconia anode. This is a promising option for high-powered applications, such as industrial uses or central electricity generating stations.

Direct-methanol fuel cell (DMFC) - A relatively new member of the fuel cell family, the direct-methanol fuel cell (DMFC) is similar to the PEM cell in that it uses a polymer membrane as an electrolyte. However, a catalyst on the DMFC anode draws hydrogen from liquid methanol, eliminating the need for a fuel reformer.

Molten carbonate fuel cell (MCFC) - The molten carbonate fuel cell uses a molten carbonate salt as the electrolyte. It has the potential to be fueled with coal-derived fuel gases or natural gas.

Alkaline fuel cell - The alkaline fuel cell uses an alkaline electrolyte such as potassium hydroxide. Originally used by NASA on missions, it is now finding applications in hydrogen-powered vehicles.

Regenerative or Reversible Fuel Cells - This special class of fuel cells produces electricity from hydrogen and oxygen, but can be reversed and powered with electricity to produce hydrogen and oxygen.

Current Status
• Currently, 48% of the worldwide production of hydrogen is via large-scale steam reforming of natural gas. Today, we safely use about 90 billion cubic meters (3.2 trillion cubic feet) of hydrogen yearly. • Direct conversion of sunlight to hydrogen using a semiconductor-based photoelectrochemical cell was recently demonstrated at 12.4% efficiency. • Hydrogen technologies are in various stages of development across the system: *Production* - Hydrogen production from conventional fossil-fuel feedstocks is commercial, and results in significant CO2 emissions. Large-scale CO2 sequestration options have not been proved and require R&D. Current commercial electrolyzers are 80-85% efficient, but the cost of hydrogen is strongly dependent on the cost of electricity. Production processes using wastes and biomass are under development, with a number of engineering scale-up projects underway. *Storage* - Liquid and compressed gas tanks are available and have been demonstrated in a small number of bus and automobile demonstration projects. Lightweight, fiber-wrapped tanks have been developed and tested for higher-pressure hydrogen storage. Experimental metal hydride tanks have been used in automobile demonstrations. Alternative solid-state storage systems using alanates and carbon nanotubes are under development. *Use* - Small demonstrations by domestic and foreign auto and bus companies have been undertaken. Small-scale power systems using fuel cells are being beta-tested. Small fuel cells for battery replacement applications have been developed. Much work remains. • Recently, there have been important advances in storage energy densities in recent years: high pressure composite tanks have been demonstrated with 7.5 wt.% storage capacity, exceeding the current DOE target, and new chemical hydrides have demonstrated a reversible capacity of 5 wt.% hydrogen. The composite tank development is a successful technology partnership among the national labs, DOE, and industry. Industrial investment in chemical hydride development recently has been initiated. • SunLine Transit receives support to operate a variety of hydrogen production processes for its bus fleet. The California Fuel Cell Partnership has installed hydrogen refueling equipment (liquid delivered to the facility) • Major industrial companies are pursuing R&D in fuel cells and hydrogen reformation technologies with a mid-term timeframe for deployment of these technologies for both stationary and vehicular applications. These companies include: ExxonMobil — Toyota Shell — Daimler-Chrysler Texaco — Honda BP — International Fuel Cells General Motors — Ballard Ford — Air Products Daimler-Chrysler — Praxair Toyota — Plug Power Systems

Technology History
• From the early 1800s to the mid-1900s, a gaseous product called town gas (manufactured from coal) supplied lighting and heating for America and Europe. Town gas is 50% hydrogen, with the rest comprised of mostly methane and carbon dioxide, with 3% to 6% carbon monoxide. Then, large natural gas fields were discovered, and networks of natural gas pipelines displaced town gas. (Town gas is still found in limited use today in Europe and Asia.) • From 1958 to present, the National Aeronautics and Space Administration (NASA) has continued work on using hydrogen as a rocket fuel and electricity source via fuel cells. NASA became the worldwide largest user of liquid hydrogen and is renowned for its safe handling of hydrogen.

- During the 20th century, hydrogen was used extensively as a key component in the manufacture of ammonia, methanol, gasoline, and heating oil. It was—and still is—also used to make fertilizers, glass, refined metals, vitamins, cosmetics, semiconductor circuits, soaps, lubricants, cleaners, margarine, and peanut butter.
- Recently, (in the late 20th century/dawn of 21st century) many industries worldwide have begun producing hydrogen, hydrogen-powered vehicles, hydrogen fuel cells, and other hydrogen products. From Japan's hydrogen delivery trucks to BMW's liquid-hydrogen passenger cars, to Ballard's fuel cell transit buses in Chicago and Vancouver, B.C.; to Palm Desert's Renewable Transportation Project, to Iceland's commitment to be the first hydrogen economy by 2030; to the forward-thinking work of many hydrogen organizations worldwide, to Hydrogen Now!'s public education work; the dynamic progress in Germany, Europe, Japan, Canada, the United States, Australia, Iceland, and several other countries launch hydrogen onto the main stage of the world's energy scene.

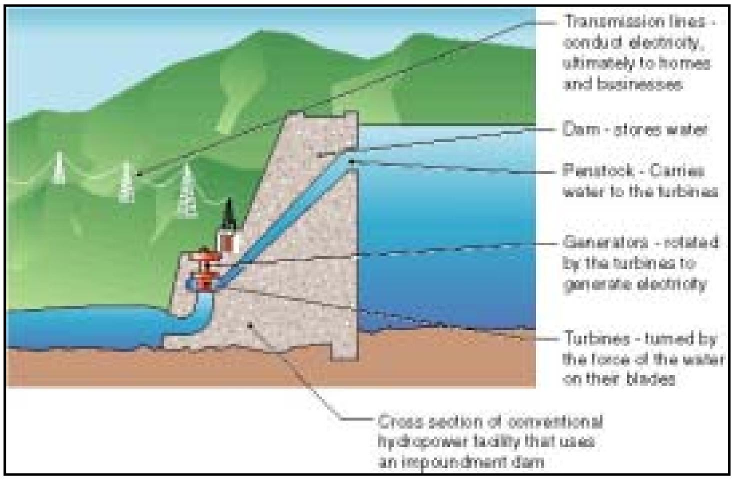
Technology Future

- Fuel cells are a promising technology for use as a source of heat and electricity for buildings, and as an electrical power source for electric vehicles. Although these applications would ideally run off pure hydrogen, in the near-term they are likely to be fueled with natural gas, methanol, or even gasoline. Reforming these fuels to create hydrogen will allow the use of much of our current energy infrastructure—gas stations, natural gas pipelines, etc.—while fuel cells are phased in. The electricity grid and the natural gas pipeline system will serve to supply primary energy to hydrogen producers.
- By 2005, if DOE R&D goals are met, (1) onboard hydrogen storage in metal hydrides at >5 wt% will be developed; (2) complete engineering design of a small-scale, mass-producible reformer for natural gas will be completed; and (3) an integrated biomass-to-hydrogen system will be demonstrated.
- By 2010, advances will be made in photobiological and photoelectrochemical processes for hydrogen production, efficiencies of fuel cells for electric power generation will increase, and advances will be made in fuel cell systems based on carbon structures, alanates, and metal hydrides
- Although comparatively little hydrogen is currently used as fuel or as an energy carrier, the long-term potential is for us to make a transition to a hydrogen-based economy in which hydrogen will join electricity as a major energy carrier. Furthermore, much of the hydrogen will be derived from domestically plentiful renewable energy or fossil resources, making the Hydrogen Economy synonymous with sustainable development and energy security.
- In summary, future fuel cell technology will be characterized by reduced costs and increased reliability for transportation and stationary (power) applications
- For a fully developed hydrogen energy system, a new hydrogen infrastructure/delivery system will be required.
- In the future, hydrogen also could join electricity as an important *energy carrier*. An energy carrier stores, moves, and delivers energy in a usable form to consumers. Renewable energy sources, like the sun or wind, can't produce energy all the time. The sun doesn't always shine nor the wind blow. But hydrogen can store this energy until it is needed and it can be transported to where it is needed.
- Some experts think that hydrogen will form the basic energy infrastructure that will power future societies, replacing today's natural gas, oil, coal, and electricity infrastructures. They see a new *hydrogen economy* to replace our current energy economies, although that vision probably won't happen until far in the future.

Advanced Hydropower

Technology Description

Advanced hydropower is new technology for producing hydroelectricity more efficiently, with improved environmental performance. Current technology often has adverse environmental effects, such as fish mortality and changes to downstream water quality and quantity. The goal of advanced hydropower technology is to maximize the use of water for hydroelectric generation while eliminating these adverse side effects—in many cases both increased energy and improved environmental conditions can be achieved.



System Concepts

- Conventional hydropower projects use either impulse or reaction turbines to convert kinetic energy in flowing or falling water into turbine torque and power. Source water may be from free-flowing rivers/streams/canals or released from upstream storage reservoirs.
- Improvements and efficiency measures can be made in dam structures, turbines, generators, substations, transmission lines, and systems operation that will help sustain hydropower's role as a clean, renewable energy source.

Representative Technologies

- Turbine designs that minimize entrainment mortality of fish during passage through the power plant.
- Autoventing turbines to increase dissolved oxygen in discharges downstream of dams.
- Reregulating and aerating weirs used to stabilize tailwater discharges and improve water quality.
- Adjustable-speed generators producing hydroelectricity over a wider range of heads and providing more uniform instream flow releases without sacrificing generation opportunities.
- New assessment methods to balance instream flow needs of fish with water for energy production.
- Advanced instrumentation and control systems that modify turbine operation to maximize environmental benefits and energy production.

Technology Applications

- Advanced hydropower products can be applied at more than 80% of existing hydropower projects (installed conventional capacity is now 78 GW); the potential market also includes 15–20 GW at existing dams without hydropower facilities (i.e., no new dams required for development) and about 30 GW at undeveloped sites that have been identified as suitable for new dams.
- The nation's largest hydropower plant is the 7,600 megawatt Grand Coulee power station on the Columbia River in Washington State. The plant is being upscaled to 10,080 megawatts, which will make it the third largest in the world.
- There would be significant environmental benefits from installing advanced hydropower technology, including enhancement of fish stocks, tailwater ecosystems, and recreational opportunities. These benefits would occur because the advanced technology reverses adverse effects of the past.
- Additional benefits would come from the protection of a wide range of ancillary benefits that are provided at hydropower projects but are at extreme risk of becoming lost in the new deregulated environment.

Current Status

- Hydropower (also called hydroelectric power) facilities in the United States can generate enough power to supply 28 million households with electricity, the equivalent of nearly 500 million barrels of oil. The total U.S. hydropower capacity—including pumped storage facilities—is about 95,000 megawatts. Researchers are working on advanced turbine technologies that will not only help maximize the use of hydropower but also minimize adverse environmental effects.
- According to EIA, hydropower provided 12.6% of the nation's electricity generating capability in 1999 and 80% of the electricity produced from renewable energy sources.
- DOE estimates current capital costs for large hydropower plants to be $1,700 to $2,300 per kW (although no new plants are currently being built in the United States and O&M is estimated at approximately 0.7 cents/kWh).
- Worldwide, hydropower plants have a combined capacity of 675,000 megawatts and annually produce more than 2.3 trillion kilowatt-hours of electricity, the energy equivalent of 3.6 billion barrels of oil.
- Existing hydropower generation is declining because of a combination of real and perceived environmental problems, regulatory pressures, and changes in energy economics (deregulation, etc.); potential hydropower resources are not being developed for similar reasons.
- The current trend is to replace hydropower with electricity from fossil fuels.
- Some new, environmentally friendly technologies are being implemented (e.g., National Hydropower Association's awards for Outstanding Stewardship of America's Rivers).
- DOE's Advanced Hydropower Turbine System (AHTS) program is also demonstrating that new turbine designs are feasible, but additional support is needed to fully evaluate these new designs in full-scale applications.
- There is insufficient understanding of how fish respond to turbulent flows in draft tubes and tailraces to support biological design criteria for those zones of power plants.
- Fish resource management agencies do not recognize that the route through turbines is acceptable for fish – this perception could be overcome if field-testing continues to show mortality through turbines is not greater than other passage routes.
- TVA's Lake Improvement Plan has demonstrated that improved turbine designs can be implemented with significant economic and environmental benefits.
- Field-testing of the Minimum Gap Runner (MGR) designs for Kaplan turbines indicate that fish survival up to 98% is possible, if conventional turbines are modified.
- FERC instituted a short-term reduction in regulatory barriers on the West Coast in 2001—this resulted in more than 100,000 MWh of additional generation and a significant shift from nonpeak to peak production, without significant adverse environmental effects.
- Regulatory trends in relicensing are to shift operation from peaking to baseload, effectively reducing the energy value of hydroelectricity; higher instream flow requirements are also reducing total energy production to protect downstream ecosystems, but scientific justification is weak.
- Frequent calls for dam removal is making relicensing more costly to dam owners.
- Regional efforts by Army Corps of Engineers and Bonneville Power Administration are producing some site-specific new understanding, especially in the Columbia River basin, but commercial applications are unlikely because of pressures from industry deregulation and environmental regulation.
- Voith-Siemans Hydro and TVA have established a limited partnership to market environmentally friendly technology at hydropower facilities. Their products were developed in part by funding provided by DOE and the Corps of Engineers, as well as private sources.
- Flash Technology is developing strobe lighting systems to force fish away from hydropower intakes and to avoid entrainment mortality in turbines.

Technology History
• Since the time of ancient Egypt, people have used the energy in flowing water to operate machinery and grind grain and corn. However, hydropower had a greater influence on people's lives during the 20th century than at any other time in history. Hydropower played a major role in making the wonders of electricity a part of everyday life and helped spur industrial development. Hydropower continues to produce 24% of the world's electricity and supply more than 1 billion people with power. • The first hydroelectric power plant was built in 1882 in Appleton, Wisconsin, to provide 12.5 kilowatts to light two paper mills and a home. Today's hydropower plants generally range in size from several hundred kilowatts to several hundred megawatts, but a few mammoth plants have capacities up to 10,000 megawatts and supply electricity to millions of people. • By 1920, 25% of electrical generation in the United States was from hydropower; and, by 1940, was 40%. • Most hydropower plants are built through federal or local agencies as part of a multipurpose project. In addition to generating electricity, dams and reservoirs provide flood control, water supply, irrigation, transportation, recreation, and refuges for fish and birds. Private utilities also build hydropower plants, although not as many as government agencies.
Technology Future
• By 2003, a quantitative understanding of the responses of fish to multiple stresses inside a turbine should be developed. Biological performance criteria for use in advanced turbine design also should be available. • By 2005, environmental mitigation studies should be available on topics such as in-stream flow needs to produce more efficient and less controversial regulatory compliance. In addition, pilot-scale testing of new runner designs, including field evaluation of environmental performance, will allow full-scale prototype construction and testing to proceed. • By 2010, full-scale prototype testing of AHTS designs should be completed, including verified biological performance of AHTS in the field. This will allow AHTS technology to be transferred to the market.

Hydroelectric Power

Market Data

U.S. Installed Capacity (MW)* *Source: Renewable Energy Project Information System (REPiS), Version 7, NREL, 2003.*

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001	2002
Annual	1,391	3,236	862	1,054	20	64	7	179	0.3	11	0.002
Cumulative	80,491	87,839	90,955	94,051	94,071	94,135	94,142	94,322	94,322	94,333	94,333

* There are an additional 24 MW of hydroelectric capacity that are not accounted for here because they have no specific online date.

Cumulative Grid-Connected Hydro Capacity (MW)* *Source: U.S. data from EIA, Annual Energy Review 2001- Table 8.7a, World Total from EIA, International Energy Annual, 1996-2001, Table 6.4. International data from International Energy Agency, Electricity Information 2002 .*

	1980	1985	1990	1995	1996	1997	1998	1999	2000	2001
U.S.										
Conventional and other Hydro	81,700	88,900	73,900	78,600	76,400	79,400	79,200	79,400	79,400	79,400
Pumped Storage	N/A	N/A	19,500	21,400	21,100	19,300	19,500	19,600	19,500	19,500
U.S. Hydro Total	81,700	88,900	93,400	100,000	97,500	98,700	98,700	99,000	98,900	98,900
OECD Europe	119,640	126,150	131,730	136,870		138,400	135,770	138,700	142,930	
IEA Europe	118,450	124,760	130,210	133,060		134,380	131,590	134,450	138,630	
Japan	18,280	19,980	20,820	21,160		21,280	21,470	21,550	22,010	
OECD Total	278,310	308,860	323,990	324,460		329,540	326,090	330,000	334,840	
IEA Total	271,060	300,860	314,590	311,300		315,510	312,200	316,120	320,890	
World Total					656,000	667,000	678,000	683,000	713,000	

*Excludes pumped storage, except for specific U.S. pumped storage capacity listed.

Annual Generation from Cumulative Installed Capacity (Billion kWh)	*Source: EIA, International Energy Annual 2001, Table 1.5.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
United States	300	325	298	335	373	376	341	334	296	224
Canada	251	301	294	332	352	347	329	342	355	328
Mexico	17	26	23	27	31	26	24	33	33	28
Japan	88	82	88	81	80	89	92	86	86	87
Western Europe	393	417	411	491	506	523	531	558	554	506
Former Soviet Union	184	205	231	238	215	216	225	227	222	240
Eastern Europe	55	50	43	34	34	36	35	35	31	32
China	58	91	125	184	185	193	203	202	220	263
Brazil	128	177	205	251	263	276	289	290	302	266
Rest of World	284	341	459	612	499	504	547	548	489	518
World Total	1,758	2,015	2,176	2,587	2,538	2,587	2,614	2,652	2,588	2,492

State Generating Capability (MW)	*Source: EIA, Electric Power Annual Vol.1: 1994 & 1999-2000- Table 2, 1995-1997- Table 5, US total from EPA 2001 Table ES*									
Top 10 States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Washington				21,054	21,038	21,054				
Oregon				9,021	9,031	9,038				
California				13,504	13,538	13,535				
New York				7,246	7,311	5,279				
Montana				2,514	2,551	2,546				
Idaho				2,416	2,418	2,432				
Arizona				2,833	2,884	2,884				
Alabama				2,959	2,962	2,881				
South Dakota				1,820	1,820	1,820				
Tennessee				3,668	3,744	3,725				
U.S. Total			93,385	99,948	97,548	98,725	98,669	98,958	98,881	98,579

State Annual Generation from Cumulative Installed Capacity* (Billion kWh)	*Source: EIA, Electric Power Annual Vol. 1: 1998-2000- Table A12, 1996-1997- Table 10, US total from EPA 2001 Table ES*									
Top 10 States	**1980**	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Washington				82.0	98.1	103.6	79.8	97.0	80.5	
Oregon				40.4	44.5	46.3	39.9	45.6	38.2	
California				47.4	44.1	39.8	50.8	40.4	39.2	
New York				23.6	26.0	27.9	28.2	23.6	24.2	
Montana				10.7	13.7	13.3	11.1	13.8	12.1	
Idaho				10.1	12.2	13.5	12.9	13.4	11.0	
Arizona				8.5	9.5	12.4	11.2	10.1	8.6	
Alabama				9.5	11.1	11.5	10.6	7.8	5.8	
South Dakota				6.0	8.0	9.0	5.8	6.7	5.7	
Tennessee				8.2	9.9	9.4	10.2	7.2	5.7	
U.S. Total			289.4	308.1	344.1	352.4	318.9	313.4	270.0	207.5

* Annual generation figures for years before 1998 do not include nonutility generation.

Annual Hydroelectric Consumption for Electric Generation (Trillion Btu)	*Source: EIA, Annual Energy Review 2001 Table 2.2b*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
U.S. Total	2,900	2,970	3,030	3,205	3,590	3,640	3,297	3,268	2,811	2,219

Note: Electric power sector and end-use sectors, conventional hydroelectric power only

Solar Buildings

Technology Description

Solar building technologies deliver heat, electricity, light, hot water, and cooling to residential and commercial buildings. By combining solar thermal and electric building technologies with very energy-efficient construction methods, lighting, and appliances, it is possible to build "Zero Energy Homes" (see photo for a demonstration-home example). Zero Energy Buildings (residential and commercial) have a zero net need for off-site energy on an annual basis and also have no carbon emissions.

System Concepts

- In solar heating systems, solar-thermal collectors convert solar energy into heat at the point of use, usually for domestic hot water and space heating.
- In solar cooling systems, solar-thermal collectors convert solar energy into heat for absorption chillers or desiccant regeneration.
- In solar lighting systems, sunlight is transmitted into the interior of buildings using glazed apertures, light pipes, and/or optical fibers.

Representative Technologies

- Active solar-heating systems use pumps and controls to circulate a heat transfer fluid between the solar collector(s) and storage. System sizes can range from 1 to 100 kW.
- Passive solar-heating systems do not use pumps and controls but rather rely on natural circulation to transfer heat into storage. System sizes can range from 1 to 10 kW.
- Transpired solar collectors heat ventilation air for industrial and commercial building applications. A transpired collector is a thin sheet of perforated metal that absorbs solar radiation and heats fresh air drawn through its perforations.
- Hybrid solar lighting systems focus concentrated sunlight on optical fibers in order to combine natural daylight with conventional illumination. Hybrid Solar Lighting (HSL) has the potential to more than double the efficiency and affordability of solar energy in commercial buildings by simultaneously separating and using different portions of the solar-energy spectrum for different end-use purposes, i.e. lighting and distributed power generation.

Technology Applications

- More than 1,000 MW of solar water-heating systems are operating successfully in the United States, generating more than 3 million MW-hrs per year.
- Based on peer-reviewed market penetration estimates, there will be approximately 1 million new solar water-heating systems installed by 2020, offering an energy savings of 0.16 quads (164 trillion Btus).
- Retrofit markets: There are 72.5 million existing single-family homes in the United States. An estimate of the potential replacement market of 29 million solar water-heating systems assumes that only 40% of these existing homes have suitable orientation and nonshading. (9.2 million replacement electric and gas water heaters.)
- New construction: In 2000, 1.2 million new single-family homes were built in the United States. Assuming 70% of these new homes could be sited to enable proper orientation of solar water-heating systems, this presents another 840,000 possible system installations annually.
- While the ultimate market for the zero-energy building concept is all new building construction; the near-term focus is on residential buildings; particularly, single-family homes in the Sunbelt areas of the

country. Of the 1.2 million new single-family homes built in the United States in 2000, 44% of these new homes were in the southern region of the country and 25% were in the western region, both areas with favorable solar resources.

Current Status

- About 1.2 million solar water-heating systems have been installed in the United States, mostly in the 1970s and 1980s. Due to relatively low energy prices and other factors, there are approximately only 8,000 installations per year.
- Typical residential solar systems use glazed flat-plate collectors combined with storage tanks to provide 40% to 70% of residential water-heating requirements. Typical systems generate 2500 kWh of energy per year and cost $1 to $2/Watt.
- Typical solar pool-heating systems use unglazed polymer collectors to provide 50% to 100% of residential pool-heating requirements. Typical systems generate 1,600 therms or 46,000 kWh of energy per year and cost $0.30 to $0.50/Watt
- Four multidisciplinary homebuilding teams have begun the initial phase of designing and constructing "Zero Energy Homes" for various new construction markets in the United States. One homebuilder (Shea Homes in San Diego) is currently building, and quickly selling, 300 houses with Zero Energy Home features—solar electric systems, solar water heating, and energy-efficient construction.
- Key companies developing or selling solar water heaters include:

Alternative Energy Technologies	Harter Industries
Aquatherm	Duke Solar
FAFCO	Heliodyne, Inc.
Radco Products	Sun Earth
Sun Systems	Thermal Conversion Technologies

Technology History

- 1890s- First commercially available solar water heaters produced in southern California. Initial designs were roof-mounted tanks and later glazed tubular solar collectors in thermosiphon configuration. Several thousand systems were sold to homeowners.
- 1900s- Solar water-heating technology advanced to roughly its present design in 1908 when William J. Bailey of the Carnegie Steel Company, invented a collector with an insulated box and copper coils.
- 1940s- Bailey sold 4,000 units by the end of WWI, and a Florida businessperson who bought the patent rights sold nearly 60,000 units by 1941.
- 1950s- Industry virtually expires due to inability to compete against cheap and available natural gas and electric service.
- 1970s- The modern solar industry began in response to the OPEC oil embargo in 1973-74, with a number of federal and state incentives established to promote solar energy. President Jimmy Carter put solar water-heating panels on the White House. FAFCO, a California company specializing in solar pool heating; and Solaron, a Colorado company that specialized in solar space and water heating, became the first national solar manufacturers in the United States. In 1974, more than 20 companies started production of flat-plate solar collectors, most using active systems with antifreeze capabilities. Sales in 1979 were estimated at 50,000 systems. In Israel, Japan, and Australia, commercial markets and manufacturing had developed with fairly widespread use.
- 1980s- In 1980, the Solar Rating and Certification Corp (SRCC) was established for testing and certification of solar equipment to meet set standards. In 1984, the year before solar tax credits expired, an estimated 100,000-plus solar hot-water systems were sold. Incentives from the 1970s helped create the 150-business manufacturing industry for solar systems with more than $800 million in annual sales

by 1985. When the tax credits expired in 1985, the industry declined significantly. During the Gulf War, sales again increased by about 10% to 20% to its peak level, more than 11,000 square feet per year (sq.ft./yr) in 1989 and 1990.

- 1990s- Solar water-heating collector manufacturing activity declined slightly, but has hovered around 6,000 to 8,000 sq.ft./yr. Today's industry represents the few strong survivors: More than 1.2 million buildings in the United States have solar water-heating systems, and 250,000 solar-heated swimming pools exist. Unglazed, low-temperature solar water heaters for swimming pools have been a real success story, with more than a doubling of growth in square footage of collectors shipped from 1995 to 2001.

Reference: American Solar Energy Society and Solar Energy Industry Association

Technology Future

- Near-term solar heating and cooling RD&D goals are to reduce the costs of solar water-heating systems to 4¢/kWh from their current cost of 8¢/kWh using polymer materials and manufacturing enhancements. This corresponds to a 50% reduction in capital cost.
- Near-term Zero Energy Building RD&D goals are to reduce the annual energy bill for an average-size home to $600 by 2004.
- Near-term solar lighting RD&D goals are to reduce the costs of solar lighting systems to 5¢/kWh.
- Zero-energy building RD&D efforts are targeted to optimize various energy efficiency and renewable energy combinations, integrate solar technologies into building materials and the building envelope, and incorporate solar technologies into building codes and standards.
- Solar heating and cooling RD&D efforts are targeted to reduce manufacturing and installation costs, improve durability and lifetime, and provide advanced designs for system integration.

Solar Buildings

Market Data

U.S. Installations (Thousands of Sq. Ft.)	*Source: EIA, Renewable Energy Annual 2001 Table 18, REA 1997, 2000, Table 16, REA 1996 Table 18, and REA 2001 Table 10.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Annual										
DHW					765	595	462	373	367	274
Pool Heaters					6,787	7,528	7,200	8,141	7,863	10,797
Total Solar Thermal[1]	18,283	19,166	11,021	7,136	7,162	7,759	7,396	8,046	7,857	10,349
Cumulative										
DHW										
Pool Heaters										
Total Solar Thermal[1]	62,829	153,035	199,459	233,386	240,548	248,307	255,703	263,749	271,606	281,955

[1] Domestic shipments - total shipments minus export shipments

U.S. Annual Shipments (Thousand Sq. Ft.)	*Source: EIA, Renewable Energy Annual 1997 Table 11, REA 1996 Table 16 and REA 2001 Table 11.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Total	19,398	N/A	11,409	7,666	7,616	8,138	7,756	8,583	8,354	11,189
Imports		N/A	1,562	2,037	1,930	2,102	2,206	2,352	2,201	3,502
Exports	1,115	N/A	245	530	454	379	360	537	496	840

U.S. Shipments by Cell Type (thousands of sq. ft.)	*Source: EIA Energy Annual Review 2001 Table 10.3 and Renewable Energy Annual 2001 Table 12.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Low-Temperature Collectors	12,233	N/A	3,645	6,813	6,821	7,524	7,292	8,152	7,948	10,919
Medium-Temperature Collectors	7,165	N/A	2,527	840	785	606	443	427	400	268
High-Temperature Collectors		N/A	5,237	13	10	7	21	4	5	2
Total	19,398	N/A	11,409	7,666	7,616	8,137	7,756	8,583	8,353	11,189

U.S. Shipments of All Solar-Thermal Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)	*Source: EIA, Renewable Energy Annual 2001 Table 18, 1997, 1999, 2000 Table 16, and REA 1998 Table 19.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Market Sector										
Residential					6,874	7,360	7,165	7,773	7,473	10,125
Commercial					682	768	517	785	810	1,012
Industrial					54	7	62	18	57	17
Utility					0	0	2	4	5	1
Other					7	2	3	2	10	35
Total					7,618	8,137	7,749	8,582	8,354	11,189
End Use										
Pool Heating					6,787	7,528	7,200	8,141	7,863	10,797
Hot Water					765	595	462	373	367	274
Space Heating					57	9	66	42	99	70
Space Cooling					0	0	0	0	0	0
Combined Space and Water Heating					2	3	16	16		
Process Heating					3	0	0	5	20	34
Electricity Generation					0	0	2	4	3	2
Other					0	1	2	2	0	0
Total					7,615	8,136	7,748	8,583	8,354	11,189

U.S. Shipments of High Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)	*Source: EIA, Renewable Energy Annual 2001 Table 18, 1997, 1999, 2000 Table 16, and REA 1998 Table 19.*									
	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Market Sector										
Residential					0	0	0	0		0
Commercial					7	7	18	0		1
Industrial					2	0	0	0		0

Utility	0	0	2	4	1
Other	0	0	1	0	0
Total	10	7	21	4	2
End Use					
Pool Heating	0	0	0	0	0
Hot Water	7	7	18	0	0
Space Heating	0	0	0	0	0
Space Cooling	0	0	0	0	0
Combined Space and Water Heating	0	0	0	0	0
Process Heating	2	0	0	0	0
Electricity Generation	0	0	2	4	2
Other	0	0	1	0	0
Total	10	7	21	4	2

U.S. Shipments of Medium-Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)

Source: EIA, Renewable Energy Annual 2001 Table 18, 1997, 1999, 2000 Table 16, and REA 1998 Table 19.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Market Sector										
Residential					728	569	355	365		238
Commercial					50	35	70	59		23
Industrial					1	0	18	0		5
Utility					0	0	0	0		0
Other					7	2	0	2		1
Total					786	606	443	426		268
End Use										
Pool Heating					21	11	36	12		16
Hot Water					754	588	384	373		231

Space Heating					6	2	13	24		9
Space Cooling					0	0	0	0		0
Combined Space and Water Heating					2	3	8	16		12
Process Heating					1	0	0	0		0
Electricity Generation					0	0	0	0		0
Other					0	1	1	2		0
Total					784	605	442	427		268

U.S. Shipments of Low-Temperature Collectors by Market Sector, and End Use (Thousands of Sq. Ft.)

Source: EIA, Renewable Energy Annual 2001 Table 18, 1997, 1999, 2000 Table 16, and REA 1998 Table 19.

	1980	**1985**	**1990**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Market Sector										
Residential					6,146	6,791	6,810	7,408		9,885
Commercial					625	726	429	726		987
Industrial					51	7	44	18		12
Utility					0	0	0	0		0
Other					0	0	2	0		34
Total					6,822	7,524	7,285	8,152		10,919
End Use										
Pool Heating					6,766	7,517	7,164	8,129		10,782
Hot Water					4	0	60	0		42
Space Heating					51	7	53	18		61
Space Cooling					0	0	0	0		0
Combined Space and Water Heating					0	0	8	0		0
Process Heating					0	0	0	5		34
Electricity Generation					0	0	0	0		0
Other					0	0	0	0		0
Total					6,821	7,524	7,285	8,152		10,919

Technology Performance

Energy Production	Source: *Arthur D. Little, Review of FY 2001 Office of Power Technology's Solar Buildings Program Planning Unit Summary, December 1999.*							
	1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Energy Savings									
DHW (kWh/yr)					2,750				
Pool Heater (therms/yr)					1,600				

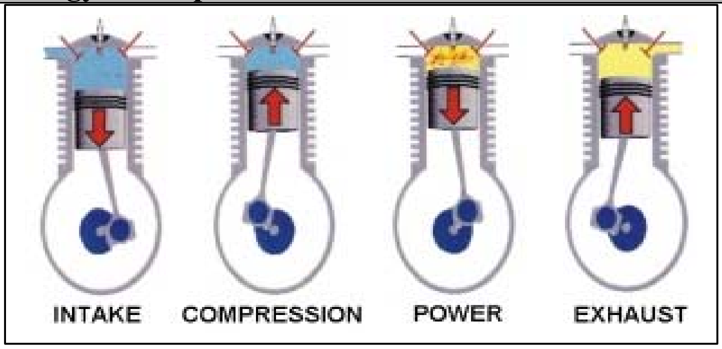
Cost	Source: *Hot-Water Heater data from Arthur D. Little, Water-Heating Situation Analysis, November 1996, page 53, and Pool-Heater data from Ken Sheinkopf, Solar Today, Nov/Dec 1997, pp. 22-25.*								
	1980	**1985**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Capital Cost* ($/System)									
Domestic Hot-Water Heater					1,900 - 2,500				
Pool Heater					3,300 - 4,000				
O&M ($/System-yr)									
Domestic Hot-Water Heater					25 - 30				
Pool Heater					0				

* Costs represent a range of technologies, with the lower bounds representing advanced technologies, such as a low-cost polymer integral collector for domestic hot-water heaters, which are expected to become commercially available after 2010.

Reciprocating Engines

Technology Description

Reciprocating engines, also known as internal combustion engines, require fuel, air, compression, and a combustion source to function. They make up the largest share of the small power generation market and can be used in a variety of applications due to their small size, low unit costs, and useful thermal output.



System Concepts

- Reciprocating engines fall into one of two categories depending on the ignition source: spark ignition (SI), typically fueled by gasoline or natural gas; or compression ignition (CI), typically fueled by diesel oil.
- Reciprocating engines also are categorized by the number of revolutions it takes to complete a combustion cycle. A two-stroke engine completes its combustion cycle in one revolution and a four-stroke engine completes the combustion process in two revolutions.

Representative Technologies

- The four-stroke SI engine has an intake, compression, power, and exhaust cycle. In the intake stroke, as the piston moves downward in its cylinder, the intake valve opens and the upper portion of the cylinder fills with fuel and air. When the piston returns upward in the compression cycle, the spark plug fires, igniting the fuel/air mixture. This controlled combustion forces the piston down in the power stroke, turning the crankshaft and producing useful shaft power. Finally the piston moves up again, exhausting the burnt fuel and air in the exhaust stroke.
- The four-stroke CI engine operates in a similar manner, except diesel fuel and air ignite when the piston compresses the mixture to a critical pressure. At this pressure, no spark or ignition system is needed because the mixture ignites spontaneously, providing the energy to push the piston down in the power stroke.
- The two-stroke engine, whether SI or CI, has a higher power density, because it requires half as many crankshaft revolutions to produce power. However, two-stroke engines are prone to let more fuel pass through, resulting in higher hydrocarbon emissions in the form of unburned fuel.

Technology Applications

- Reciprocating engines can be installed to accommodate baseload, peaking, or standby power applications. Commercially available engines range in size from 50 kW to 6.5 MW making them suitable for many distributed-power applications. Utility substations and small municipalities can install engines to provide baseload or peak shaving power. However, the most promising markets for reciprocating engines are on-site at commercial, industrial, and institutional facilities. With fast start-up time, reciprocating engines can play integral backup roles in many building energy systems. On-site reciprocating engines become even more attractive in regions with high electric rates (energy/demand charges).
- When properly treated, the engines can run on fuel generated by waste treatment (methane) and other biofuels.
- By using the recuperators that capture and return waste exhaust heat, reciprocating engines can be used in combined heat and power (CHP) systems to achieve energy efficiency levels approaching 80%. In fact, reciprocating engines make up a large portion of the CHP or cogeneration market.

Current Status

- Commercially available engines have electrical efficiencies (LHV) between 37% and 40% and yield NOx emissions of 1-2 grams per horsepower hour (hp-hr).
- Installed cost for reciprocating engines range between $600 and $1,600/ kW depending on size and whether the unit is for a straight generation or cogeneration application. Operating and maintenance costs range 2 cents to 2.5 cents/kWh.
- Exhaust temperature for most reciprocating engines is 700-1200° F in non-CHP mode and 350-500°F in a CHP system after heat recovery.
- Noise levels with sound enclosures are typically between 70-80 dB.
- The reciprocating-engine systems typically include several major parts: fuel storage, handling, and conditioning, prime mover (engine), emission controls, waste recovery (CHP systems) and rejections (radiators), and electrical switchgear.
- Annual shipments of reciprocating engines (sized 10GW or less) have almost doubled to 18 GW between 1997 and 2000. The growth is overwhelming in the diesel market, which represented 16 GW shipments compared with 2 GW of natural gas reciprocating engine shipments in 2000.

(*Source: Diesel and Gas Turbine Worldwide*).

Key indicators for stationary reciprocating engines:

Installed Worldwide Capacity	Installed US Capacity	Number of CHP sites using Recips in the U.S.
146 GW	52 GW	1,022

Source: Distributed Generation: The Power Paradigm for the New Millenium, 2001

Manufacturers of reciprocating engines include:

Caterpillar	Jenbacher
Cummins	Wartsila
Detroit Diesel	Waukesha

Technology History

- Natural gas-reciprocating engines have been used for power generation since the 1940s. The earliest engines were derived from diesel blocks and incorporated the same components of the diesel engine. Spark plugs and carburetors replaced fuel injectors, and lower compression–ratio pistons were substituted to run the engine on gaseous fuels. These engines were designed to run without regard to fuel efficiency or emission levels. They were used mainly to produce power at local utilities and to drive pumps and compressors.
- In the mid-1980s, manufacturers were facing pressure to lower NOx emissions and increase fuel economy. Leaner air-fuel mixtures were developed using turbochargers and charge air coolers, and in combination with lower in-cylinder fire temperatures, the engines reduced NOx from 20 to 5 g/bhp-hr. The lower in-cylinder fire temperatures also meant that the BMEP (Brake Mean Effective Pressure) could increase without damaging the valves and manifolds.
- Reciprocating-engine sales have grown more then five-fold from 1988 (2 GW) to 1998 (11.5 GW). Gas-fired engine sales in 1990 were 4% compared to 14% in 1998. The trend is likely to continue for gas-fired reciprocating engines due to strict air-emission regulations and because performance has been steadily improving for the past 15 years.

Technology Future
The U.S. Department of Energy, in partnership with the Gas Technology Institute, the Southwest Research Institute, and equipment manufacturers, supports the Advanced Reciprocating Engines Systems (ARES) consortium, aimed at further advancing the performance of the engine. Performance targets include: *High Efficiency*- Target fuel-to-electricity conversion efficiency (LHV) is 50 % by 2010. *Environment* – Engine improvements in efficiency, combustion strategy, and emissions reductions will substantially reduce overall emissions to the environments. The NOx target for the ARES program is 0.1 g/hp-hr, a 90% decrease from today's NOx emissions rate. *Fuel Flexibility* – Natural gas-fired engines are to be adapted to handle biogas, renewables, propane and hydrogen, as well as dual fuel capabilities. *Cost of Power* – The target for energy costs, including operating and maintenance costs is 10 % less than current state-of-the-art engine systems. *Availability, Reliability, and Maintainability* – The goal is to maintain levels equivalents to current state-of-the-art systems. Other R&D directions include: new turbocharger methods, heat recovery equipment specific to the reciprocating engine, alternate ignition system, emission-control technologies, improved generator technology, frequency inverters, controls/sensors, higher compression ratio, and dedicated natural-gas cylinder heads.

Reciprocating Engines

Technology Performance

Power Ranges (kW) of Selected Manufacturers — Source: Manufacturer Specs

	Low	High
Caterpillar	150	3,350
Waukesha	200	2,800
Cummins	5	1,750
Jenbacher	200	2,600
Wartsila	500	5,000

Market Data

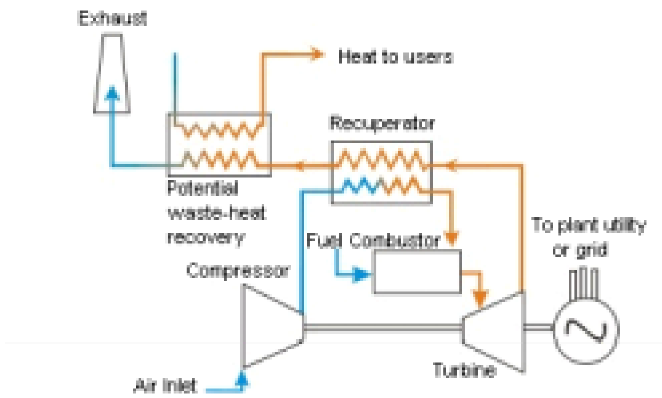
Market Shipments
(GW of units under 10 MW in size)

Source: Debbie Haught, DOE, communication 2/26/02 - from Diesel and Gas Turbine Worldwide.

	1996	1997	1998	1999	2000
Diesel Recips	7.96	7.51	8.23	10.02	16.46
Gas Recips	0.73	1.35	1.19	1.63	2.07

Microturbines

Technology Description



Microturbines are small combustion turbines of a size comparable to a refrigerator and with outputs of 25 kW to 500 kW. They are used for stationary energy generation applications at sites with space limitations for power production. They are fuel-flexible machines that can run on natural gas, biogas, propane, butane, diesel, and kerosene. Microturbines have few moving parts, high efficiency, low emissions, low electricity costs, and waste heat utilization opportunities; and are lightweight and compact in size. Waste heat recovery can be used in combined heat and power (CHP) systems to achieve energy efficiency levels greater than 80%.

System Concepts

- Microturbines consist of a compressor, combustor, turbine, alternator, recuperator, and generator.
- Microturbines are classified by the physical arrangement of the component parts: single shaft or two-shaft, simple cycle or recuperated, inter-cooled, and reheat. The machines generally operate at more than 40,000 rpm.
- A single shaft is the more common design because it is simpler and less expensive to build. Conversely, the split shaft is necessary for machine-drive applications, which do not require an inverter to change the frequency of the AC power.
- Efficiency gains can be achieved with greater use of materials like ceramics, which perform well at higher engine-operating temperatures.

Representative Technologies

- Microturbines in a simple cycle, or unrecuperated, turbine; compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gas is allowed to expand through a turbine to perform work. Simple-cycle microturbines have lower cost, higher reliability, and more heat available for CHP applications than recuperated units.
- Recuperated units use a sheet-metal heat exchanger that recovers some of the heat from an exhaust stream and transfers it to the incoming air stream. The preheated air is then used in the combustion process. If the air is preheated, less fuel is necessary to raise its temperature to the required level at the turbine inlet. Recuperated units have a higher efficiency and thermal-to-electric ratio than unrecuperated units, and yield 30-40% fuel savings from preheating.

Technology Applications

- Microturbines can be used in a wide range of applications in the commercial, industrial, and institutional sectors, microgrid power parks, remote off-grid locations, and premium power markets.
- Microturbines can be used for backup power, baseload power, premium power, remote power, cooling and heating power, mechanical drive, and use of wastes and biofuels.
- Microturbines can be paired with other distributed energy resources such as energy-storage devices and thermally activated technologies.

Current Status

- Microturbine systems are just entering the market and the manufacturers are targeting both traditional and nontraditional applications in the industrial and buildings sectors, including CHP, backup power, continuous power generation, and peak shaving.
- The most popular microturbine installed to date is the 30-kW system manufactured by Capstone.
- The typical 30-60 kW unit cost averages $1,000/kW. For gas-fired microturbines, the present installation cost (site preparation and natural gas hookup) for a typical commercial site averages $8,200.
- Honeywell pulled out of the microturbine business in December 2001, leaving the following manufacturers in the microturbine market:

Capstone Turbine Corporation	Ingersoll-Rand
DTE Energy Technologies	UTRC
Elliot Energy Systems	Bowman Power
Turbec	

- Capstone, Ingersoll-Rand, Elliott, and Turbec combined have shipped more than 2,100 units (156 MW) worldwide during the past four years.

Technology History

- Microturbines represent a relatively new technology, which is just making the transition to commercial markets. The technology used in microturbines is derived from aircraft auxiliary power systems, diesel-engine turbochargers, and automotive designs.
- In 1988, Capstone Turbine Corporation began developing the microturbine concept; and in 1998, Capstone was the first manufacturer to offer commercial power products using microturbine technology.

Technology Future

- The market for microturbines is expected to range from $2.4-to-$8 billion by 2010, with 50% of sales concentrated in North America.
- The acceptable cost target for microturbine energy is $0.05/kWh, which would present a cost advantage over most nonbaseload utility power.
- The next generation of "ultra-clean, high-efficiency" microturbine product designs will focus on the following DOE performance targets:
  - High Efficiency — Fuel-to-electricity conversion efficiency of at least 40%.
  - Environment — NOx < 7 ppm (natural gas).
  - Durability — 1,000 hours of reliable operations between major overhauls and a service life of at least 45,000 hours.
  - Cost of Power — System costs < $500/kW, costs of electricity that are competitive with alternatives (including grid) for market applications by 2005 (for units in the 30-60 kW range)
  - Fuel Flexibility — Options for using multiple fuels including diesel, ethanol, landfill gas, and biofuels.

Microturbines

Market Data

Microturbine Shipments	Source: Debbie Haught, communications 2/26/02. Capstone sales reported in Quarterly SEC filings, others estimated.			
# of units	**1998**	**1999**	**2000**	**2001**
Capstone	2	211	790	1033
Other Manufacturers				120
MW				
Capstone		6	23.7	38.1
Other Manufacturers				10.2

Technology Performance

Source: Manufacturer Surveys, Arthur D. Little (ADL) estimates.

Current System Efficiency (%)	LHV: 17-20% unrecuperated, 25-30%+ recuperated	
Lifetime (years)	5-10 years, depending on duty cycle	
Emissions (natural gas fuel)	Current	Future (2010
CO_2	670 - 1,180 g/kWh (17-30% efficiency)	
SO_2	Negligible (natural gas)	Negligible
NO_x	9-25 ppm	<9 ppm
CO	25-50 ppm	<9 ppm
PM	Negligible	Negligible
Typical System Size	Current Products: 25-100 kW Units can be bundled or "ganged" to produce power in larger increments	Future Products: up to 1 MW
Maintenance Requirements (Expected)	10,000-12,000 hr before major overhaul (rotor replacement)	
Footprint [ft^2/kW]	0.2-0.4	

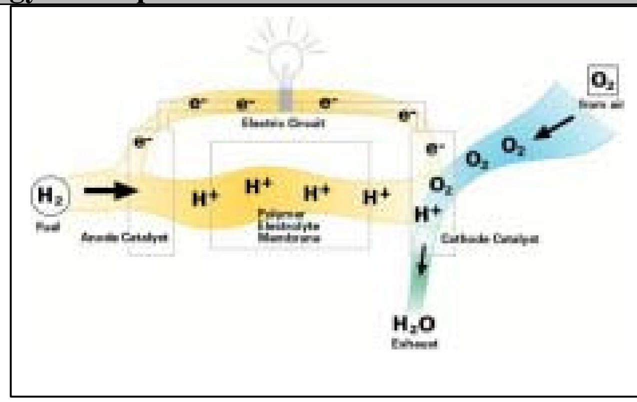
Technology Performance

Sources: Debbie Haught, DOE, communication 2/26/02 and Energetics, Inc. *Distributed Energy Technology Simulator: Microturbine Validation*, July 12 2001.

	Capstone Turbine Corporation		Elliot Energy Systems	Ingersoll-Rand Energy Services		Turbec	DTE Energy Technologies
Model Name	Model 330	Capstone 60	TA-80	PowerWorks			ENT 400 recuperated
Size	30 kW	60 kW	80 kW	70 kW		100 kW	300 kW
Voltage	400-480 VAC					400 VAC	480/277 VAC
Fuel Flexibility	natural gas, medium Btu gas, diesel, kerosene		natural gas	natural gas		natural gas, biogas, ethanol, diesel	natural gas (diesel, propane future)
Fuel Efficiency (cf/kWh)	13.73	14.23				11.2	
Efficiency	26% (+/-2%)	28% (+/- 2%)	28%	30-33%		30%	28% (+/- 2%)
	70-90% CHP	70-90% CHP	80% CHP			80% CHP	74% CHP
Emissions	NO_x <9ppmV @15% O_2		NO_x diesel <60ppm, NO_x NG <25ppm, CO diesel <400ppm, CO NG <85ppm	NO_x <9ppmV @15% O_2, CO <9ppmV @15% O_2		NO_x <15ppmV @15% O_2, CO <15ppm, UHC <10ppm	NOx <9ppmV @15% O_2
Units Sold	1999: 211 units			2000: 2 precommercial units, expected commercial in 2001		2000: 20 units in the European market	Available late 2001
	2000: 790 units						
	2001: 1,033 units		2001: 100 units				
Unit Cost	$1000/kW					$75,000	
Cold Start-Up Time	3 min						3 min emergency, 7 min normal
Web site	www.capstone.com		www.elliott-turbo.com/new/products_microtubines.html	www.irco.com/energysystems/powerworks.html		www.turbec.com	www.dtetech.com/energynow/portfolio/2_1_4.asp

Fuel Cells

Technology Description



A fuel cell is an electrochemical energy conversion device that converts hydrogen and oxygen into electricity and water. This unique process is practically silent, nearly eliminates emissions, and has no moving parts.

System Concepts

- Similar to a battery, fuel cells have an anode and a cathode separated by an electrolyte.
- Hydrogen enters the anode and air (oxygen) enters the cathode. The hydrogen and oxygen are separated into ions and electrons, in the presence of a catalyst. Ions are conducted through the electrolyte while the electrons flow through the anode and the cathode via an external circuit. The current produced can be utilized for electricity. The ions and electrons then recombine, with water and heat as the only byproducts.
- Fuel cell systems today typically consist of a fuel processor, fuel cell stack, and power conditioner. The fuel processor, or reformer, converts hydrocarbon fuels to a mixture of hydrogen-rich gases and, depending on the type of fuel cell, can remove contaminants to provide pure hydrogen. The fuel cell stack is where the hydrogen and oxygen electrochemically combine to produce electricity. The electricity produced is direct current (DC) and the power conditioner converts the DC electricity to alternating current (AC) electricity, for which most of the end-use technologies are designed. As a hydrogen infrastructure emerges, the need for the reformer will disappear as pure hydrogen will be available near point of use.

Representative Technologies

Fuel cells are categorized by the kind of electrolyte they use.

Alkaline Fuel Cells (AFCs) were the first type of fuel cell to be used in space applications. AFCs contain a potassium hydroxide (KOH) solution as the electrolyte and operate at temperatures between 60 and 250°C (140 to 482°F). The fuel supplied to an AFC must be pure hydrogen. Carbon monoxide poisons an AFC, and carbon dioxide (even the small amount in the air) reacts with the electrolyte to form potassium carbonate.

Phosphoric Acid Fuel Cells (PAFCs) were the first fuel cells to be commercialized. These fuel cells operate at 150-220°C (302-428°F) and achieve 35 to 45% fuel-to-electricity efficiencies LHV.

Proton Exchange Membrane Fuel Cells (PEMFCs) operate at relatively low temperatures of 70-100°C (158-212°F), have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications where quick start-up is required (e.g., transportation and power generation). The PEM is a thin fluorinated plastic sheet that allows hydrogen ions (protons) to pass through it. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that are active catalysts.

Molten Carbonate Fuel Cell (MCFC) technology has the potential to reach fuel-to-electricity efficiencies of 45 to 60% on a lower heating value basis (LHV). Operating temperatures for MCFCs are around 650° C (1,200°F), which allows total system thermal efficiencies up to 85% LHV in combined-cycle applications. MCFCs have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products.

Solid Oxide Fuel Cells (SOFCs) operate at temperatures up to 1,000°C (1,800°F), which further enhances combined-cycle performance. A solid oxide system usually uses a hard ceramic material instead of a liquid electrolyte. The solid-state ceramic construction enables the high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability. As with MCFCs, SOFCs are capable of fuel-to-electricity efficiencies of 45 to 60% LHV and total system thermal efficiencies up to 85% LHV in combined-cycle applications.

Technology Applications

- Fuel cell systems can be sized for grid-connected applications or customer-sited applications in residential, commercial, and industrial facilities. Depending on the type of fuel cell (most likely SOFC and MCFC), useful heat can be captured and used in combined heat and power systems (CHP).
- Premium power applications are an important niche market for fuel cells. Multiple fuel cells can be used to provide extremely high (more then six-nines) reliability and high-quality power for critical loads.
- Data centers and sensitive manufacturing processes are ideal settings for fuel cells.
- Fuel cells also can provide power for vehicles and portable power. PEMFCs are a leading candidate for powering the next generation of vehicles. The military is interested in the high-efficiency, low-noise, small-footprint portable power.

Current Status

- Fuel cells are still too expensive to compete in widespread domestic and international markets without significant subsidies.
- PAFC – More than 170 PAFC systems are in service worldwide, with those installed by ONSI having surpassed 2 million total operating hours with excellent operational characteristics and high availability.

Economic Specifications of the PAFC (200 kW)

Expense	Description	Cost
Capital Cost	1 complete PAFC power plant	$850,000
Installation	Electrical, plumbing, and foundation	$40,000
Operation	Natural gas costs	$5.35/MMcf
Minor Maintenance	Service events, semiannual and annual maintenance	$20,000/yr
Major Overhaul	Replacement of the cell stack	$320,000/5 yrs

Source: Energetics, *Distributed Energy Technology Simulator: Phosphoric Acid Fuel Cell Validation*, May 2001.

PEMFC – Ballard's first 250 kW commercial unit is under test. PEM systems up to 200 kW are also operating in several hydrogen-powered buses. Most units are small (<10 kW). PEMFCs currently cost several thousand dollars per kW.
SOFC – A small, 25 kW natural gas tubular SOFC systems has accumulated more than 70,000 hours of operations, displaying all the essential systems parameters needed to proceed to commercial configurations. Both 5 kW and 250 kW models are in demonstration.
MCFC – 50 kW and 2 MW systems have been field-tested. Commercial offerings in the 250 kW-2 MW range are under development.

Some fuel cell developers include:

Avista Laboratories	H Power
Ball Aerospace and Technologies Corp.	IdaTech
Ballard Power Systems, Inc	M-C Power
BCS Technology, Inc.	ONSI Corporation (IFC/United Technologies)
Ceramatec	Plug Power, LLC
DCH Technology, Inc	Proton Energy Systems
FuelCell Energy	Siemens Westinghouse Power Corporation

Fuel Cell Type	Electrolyte	Operating Temp (°C)	Electrical Efficiency (% LHV)	Commercial Availability	Typical Unit Size Range	Start-up time (hours)
AFC	KOH	60-250		1960s		
PEMFC	Nafion	70-100	35-45	2000-2001	5-250 kW	< 0.1
PAFC	Phosphoric Acid	150-220	35-45	1993	200 kW	1-4
MCFC	Lithium, potassium, carbonate salt	600-650	45-60	Post 2003	250 kW-2 MW	5-10
SOFC	Yttrium & zirconium oxides	800-1000	45-60	Post 2003	5-250 kW	5-10

Sources: Anne Marie Borbely and Jan F. Kreider. *Distributed Generation: The Power Paradigm for the New Millennium*, CRC Press, 2001, and Arthur D. Little, Distributed Generation Primer: Building the Factual Foundation (multiclient study), February 2000

Technology History

- In 1839, William Grove, a British jurist and amateur physicist, first discovered the principle of the fuel cell. Grove utilized four large cells, each containing hydrogen and oxygen, to produce electric power which was then used to split the water in the smaller upper cell into hydrogen and oxygen.
- In the 1960s, alkaline fuel cells were developed for space applications that required strict environmental and efficiency performance. The successful demonstration of the fuel cells in space led to their serious consideration for terrestrial applications in the 1970s.
- In the early 1970s, DuPont introduced the Nafion® membrane, which has traditionally become the electrolyte for PEMFC.
- In 1993, ONSI introduced the first commercially available PAFC. Its collaborative agreement with the U.S. Department of Defense enabled more than 100 PAFCs to be installed and operated at military installations.
- The emergence of new fuel cell types (SOFC, MCFC) in the past decade has led to a tremendous expansion of potential products and applications for fuel cells.

Technology Future

- According to the Business Communications Company, the market for fuel cells was about $218 million in 2000, will increase to $2.4 billion by 2004, and will reach $7 billion by 2009.
- Fuel cells are being developed for stationary power generation through a partnership of the U.S DOE and the private sector.
- Industry will introduce high-temperature natural gas-fueled MCFC and SOFC at $1,000 -$1,500 per kW that are capable of 60% efficiency, ultra-low emissions, and 40,000 hour stack life.
- DOE is also working with industry to test and validate the PEM technology at the 1–kW level and to transfer technology to the Department of Defense. Other efforts include raising the operating temperature of the PEM fuel cell for building, cooling, heating, and power applications and improve reformer technologies to extract hydrogen from a variety of fuels, including natural gas, propane, and methanol.

Fuel Cells

Technology Performance

Source: Arthur D. Little (ADL) estimates, survey of equipment manufacturers.

Only industrial applications; table does not address residential/commercial-scale fuel cells.

Technology	Size Range (kW)	2000 Characteristics: Installed Cost ($/kW) Low	Installed Cost ($/kW) High	Non-Fuel O&M (cents/kWh) Low	Non-Fuel O&M (cents/kWh) High	Electrical Efficiency (LHV) High	Electrical Efficiency (LHV) Low	2005 Characteristics: Installed Cost ($/kW) Low	Installed Cost ($/kW) High	Non-Fuel O&M (cents/kWh) Low	Non-Fuel O&M (cents/kWh) High	Electrical Efficiency (LHV) High	Electrical Efficiency (LHV) Low
Low Temperature Fuel Cell (PEM)	200-250	2,000	3,000	1.5	2.0	40%	30%	1,000	2,000	1.0	1.8	43%	33%
High Temperature Fuel Cell (SOFC & MCFC)	250-1,000	NA						1,500	2,000	1.0	2.0	55%	45%

Source: Energetics, *Distributed Energy Technology Simulator: PAFC Validation,* May 2001.

	Size (kW)	Capital Cost	Installation (Site Preparation)	Operation Costs (Natural Gas)	Minor Maintenance	Major Overhaul
Installation of a commercially available PAFC	200	$850,000	$40,000	$5.35/MMcf	$20,000/yr	$320,000/5 yrs

Technology Performance

There have been more than 25 fuel cell demonstrations funded by the private sector, the government, or a cofunded partnership of both. The objectives for most have been to validate a specific technology advance or application, and most of these demonstrations have been funded by the Office of Fossil Energy.

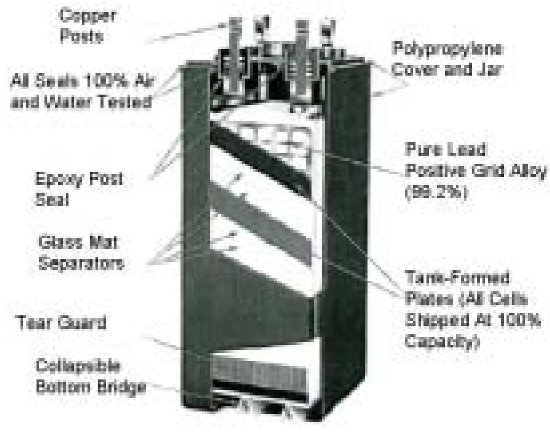
This is a listing of the demonstrations that have taken place between 1990 and today that have been published. All of the demonstrations were deemed a success, even if the testing had to end before its scheduled completion point. All of the manufacturers claimed they learned a great deal from each test. All the OPT-funded demonstrations were used to prove new higher performance-based technology either without lower catalyst levels, metal separator plates, carbon paper in lieu of machined carbon plates, or new membrane materials. Only the Plug Power fuel cell tested for the Remote Power Project failed, due to an electrical fire.

Fuel Cell Type	Company	Objective
Phosphoric Acid Fuel Cell	UT Fuel Cells (IFC)/FE	12.5 kW prototype using a new membrane assembly. (60 units) 40 kW power plant (46 units) 100 kW prototype for Georgetown Bus. (2 units) Methanol 200 kW first manufacturing prototype for PC25 (4 units) including natural gas reformer
Phosphoric Acid Fuel Cell	IFC/OPT	200 kW hydrogen version of PC 25 without a reformer, lower cost assembly
Solid Oxide	Westinghouse/FE	2 MW SOFC at Toshiba for fuels and tubular geometry testing 100 kW plannar unit to test seals, Netherlands 250 kW hybrid(57/50) w/turbine SoCal Ed 250 kW tubular SOFC combined heat and power, Ontario Power
Molten Carbonate	Fuel Cell Energy/FE	250 kW 8,800 hours Danbury Ct. first precommercial prototype 3 MW four years to build, Lexington Clean Coal Project 2 MW San Diego failed early
Proton Exchange Membrane	Plug Power/OTT Plug Power/OPT	10 kW prototype for vehicles 50 kW unsuccessful 25 kW prototype for Alaska, integrated with diesel reformer 50 kW prototype for Las Vegas refueling station, integrated with natural gas reformer

Proton Exchange Membrane	IFC/OTT	10 kW prototype sent to LANL for evaluation 50 kW prototype sent to GM for evaluation, reduced Pt catalyst 75 kW prototype installed in Hundai SUV, prototype for all transportation devices
Proton Exchange Membrane	Schatz Energy Center/OPT	(3) 5 kW Personal Utility Vehicles, (1) 15 kW Neighborhood Electric Vehicle Palm Desert each incorporated different levels of Pt catalyst, different membranes, all hydrogen fueled 1.3 kW Portable Power Unit
Proton Exchange Membrane	Enable/OPT	(3) 100 W Portable Power Units to demonstrate radial design (2) 1.5 kW Portable Power Units incorporating the LANL adiabatic fuel cell design (1) 1 kW “air breather” design for wheelchair
Proton Exchange Membrane	Ballard: no DOE funds	(6) 250 kW 40 foot passenger buses, hydrogen fueled: 3 Chicago, 2 Vancouver, 1 Palm Desert (1) 100 kW powerplant for Ford “Think” car (1) 250 kW stationary powerplant new manufacturing design
Proton Exchange Membrane	Nuvera/OPT	3 kW powerplant using metal separator plate technology for Alaska evaluated by SNL and University of Alaska
Proton Exchange Membrane	Coleman Powermate/Ballard no DOE funds	(3) 1.3 kW precommercial prototype UPS systems, metal hydride storage, under evaluation at United Laboratories for rating
Proton Exchange Membrane	Reliant Energy	7.5 kW precommercial prototype of radial stack geometry with conductive plastic separator plates
Alkaline	Zetec	25 kW precommercial prototype to demonstrate regenerative carbon dioxide scrubber
Alkaline	Hamilton Standard/IFC	(100) 12.5 kW commercial units for NASA
Alkaline	Union Carbide	(2) 50 kW fuel cells for GM van and car

Batteries

Technology Description



Batteries are likely the most widely known type of energy storage. They all store and release electricity through electrochemical processes and come in a variety of shapes and sizes. Some are small enough to fit on a computer circuit board while others are large enough to power a submarine. Some batteries are used several times a day while others may sit idle for 10 or 20 years before they are ever used. Obviously for such a diversity of uses, a variety of battery types are necessary. But all of them work from the same basic principles.

System Concepts
Battery electrode plates, typically consisting of chemically reactive materials, are placed in an electrolyte, which facilitates the transfer of ions in the battery. The negative electrode gives up electrons during the discharge cycle. This flow of electrons creates electricity that is supplied to any load connected to the battery. The electrons are then transported to the positive electrode. This process is reversed during charging. Batteries store and deliver direct current (DC) electricity. Thus, power-conversion equipment is required to connect a battery to the alternating current (AC) electric grid.

Representative Technologies

- The most mature battery systems are based on lead-acid technology. There are two major kinds of lead acid batteries: flooded lead acid batteries and valve-regulated-lead-acid (VRLA) batteries.
- There are several rechargeable, advanced batteries under development for stationary and mobile applications, including lithium-ion, lithium polymer, nickel metal hydride, zinc-air, zinc-bromine, sodium sulfur, and sodium bromide.
- These advanced batteries offer potential advantages over lead acid batteries in terms of cost, energy density, footprint, lifetime, operating characteristics reduced maintenance, and improved performance.

Technology Applications

- Lead-acid batteries are the most common energy storage technology for stationary and mobile applications. They offer maximum efficiency and reliability for the widest variety of stationary applications: telecommunications, utility switchgear and control, uninterruptible power supplies (UPS), photovoltaic, and nuclear power plants. They provide instantaneous discharge for a few seconds or a few hours.
- Installations can be any size. The largest system to date is 20 MW. Lead-acid batteries provide power quality, reliability, peak shaving, spinning reserve, and other ancillary services. The disadvantages of the flooded lead-acid battery include the need for periodic addition of water, and the need for adequate ventilation since the batteries can give off hydrogen gas when charging.
- VRLA batteries are sealed batteries fitted with pressure-release valves. They have been called low-maintenance batteries because they do not require periodic adding of water. They can be stacked horizontally as well as vertically, resulting in a smaller footprint than flooded lead-acid batteries. Disadvantages include higher cost and increased sensitivity to the charging cycle used. High temperature results in reduced battery life and performance.

- Several advanced "flow batteries" are under development. The zinc-bromine battery consists of a zinc positive electrode and a bromine negative electrode separated by a microporous separator. An aqueous solution of zinc/bromide is circulated through the two compartments of the cell from two separate reservoirs. Zinc-bromine batteries are currently being demonstrated in a number of hybrid installations, with microturbines and diesel generators. Sodium bromide/sodium bromine batteries are similar to zinc-bromine batteries in function and are under development for large-scale, utility applications. The advantages of flow-battery technologies are low cost, modularity, scalability, transportability, low weight, flexible operation, and all components are easily recyclable. Their major disadvantages are a relatively low cycle efficiency.
- Other advanced batteries include the lithium-ion, lithium-polymer, and sodium-sulfur batteries. The advantages of lithium batteries include their high specific energy (four times that of lead-acid batteries) and charge retention. Sodium sulfur batteries operate at high temperature and are being tested for utility load-leveling applications.

Current Status

- Energy storage systems for large-scale power quality applications (~10 MW) are economically viable now with sales from one manufacturer doubling from 2000 to 2001.
- Lead-acid battery annual sales have tripled between 1993 and 2000. The relative importance of battery sales for switchgear and UPS applications shrunk during this period from 45% to 26% of annual sales by 2000. VRLA and flooded battery sales were 534 and 171 million dollars, respectively, in 2000. Recently, lead-acid battery manufacturers have seen sales drop with the collapse of the telecommunications bubble in 2001. They saw significant growth in sales in 2000, due to the demand from communications firms, and invested in production and marketing in anticipation of further growth.
- Many manufacturers have been subject to mergers and acquisitions. A few dozen manufacturers in the United States and abroad still make batteries.
- Government and private industry are currently developing a variety of advanced batteries for transportation and defense applications: lithium-ion, lithium polymer, nickel metal hydride, sodium metal chloride, sodium sulfur, and zinc bromine.
- Rechargeable lithium batteries already have been introduced in the market for consumer electronics and other portable equipment.
- There are two demonstration sites of ZBB's Zinc Bromine batteries in Michigan and two additional ones in Australia.

Representative Current Manufacturers

Flooded	VRLA	Nickel Cadmium, Lithium Ion	Zinc Bromine
East Penn Exide Rolls Trojan	Hawker GNB Panasonic Yuasa	SAFT Sanyo Panasonic	Medentia Powercell ZBB

Technology History

- Most historians date the invention of batteries to about 1800 when experiments by Alessandro Volta resulted in the generation of electrical current from chemical reactions between dissimilar metals.
- Secondary batteries date back to 1860 when Raymond Gaston Planté invented the lead-acid battery. His cell used two thin lead plates separated by rubber sheets. He rolled the combination up and immersed it in a dilute sulfuric acid solution. Initial capacity was extremely limited since the positive plate had little active material available for reaction.

- Others developed batteries using a paste of lead oxides for the positive plate active materials. This allowed much quicker formation and better plate efficiency than the solid Planté plate. Although the rudiments of the flooded lead-acid battery date back to the 1880s, there has been a continuing stream of improvements in the materials of construction and the manufacturing and formation processes.
- Since many of the problems with flooded lead-acid batteries involved electrolyte leakage, many attempts have been made to eliminate free acid in the battery. German researchers developed the gelled-electrolyte lead-acid battery (a type of VRLA) in the early 1960s. Working from a different approach, Gates Energy Products developed a spiral-wound VRLA cell, which represents the state of the art today.

Technology Future

- Lead-acid batteries provide the best long-term power in terms of cycles and float life and, as a result, will likely remain a strong technology in the future.
- Energy storage and battery systems in particular will play a significant role in the Distributed Energy Resource environment of the future. Local energy management and reliability are emerging as important economic incentives for companies.
- A contraction in sales of lead-acid batteries that began in 2001 was expected to continue over the next few years until 9/11 occurred. Military demand for batteries may drastically alter the forecast for battery sales.
- Battery manufacturers are working on incremental improvements in energy and power density.

The battery industry is trying to improve manufacturing practices and build more batteries at lower costs to stay competitive. Gains in development of batteries for mobile applications will likely crossover to the stationary market.

- Zinc Bromine batteries are expected to be commercialized in 2003 with a target cost of $400/kWh.

A 10 MW-120 MWh sodium bromide system is under construction by the Tennessee Valley Authority
A 40 MW nickel cadmium system is being built for transmission-line support and stabilization in Alaska.

Batteries

Market Data

Recent Battery Sales Source: Battery Council International, Annual Sales Summary, October 2001.

	1993	2000	Growth
Flooded Batteries (Million $)	156.9	533.5	340%
VRLA Batteries (Million $)	79.6	170.6	214%
Total Lead-Acid Batteries (Million $)	236.5	704.1	298%

Percent Communications	58%	69%
Percent Switchgear/UPS	45%	26%

Market Predictions Source: Sandia National Laboratories, Battery Energy Storage Market Feasibility Study, September 1997.

Year	MW	($ Million)
2000	496	372
2005	805	443
2010	965	434

Technology Performance

Grid-Connected Energy Storage Technologies Costs and Efficiencies Source: Sandia National Laboratories, Characteristics and Technologies for Long- vs. Short-Term Energy Storage, March 2001.

Energy-Storage System	Energy Related Cost ($/kWh)	Power Related Cost ($/kW)	Balance of Plant ($/kWh)	Discharge Efficiency
Lead-acid Batteries				
low	175	200	50	0.85
average	225	250	50	0.85
high	250	300	50	0.85
Power-Quality Batteries	100	250	40	0.85
Advanced Batteries	245	300	40	0.7

Technology Performance

Off-Grid Storage Applications, Their Requirements, and Potential Markets to 2010 According to Boeing Source: Sandia National Laboratories, Energy Storage Systems Program Report for FY99, June 2000.

Application	Single Home: Developing Community	Developing Community: No Industry	Developing Community: Light Industry	Developing Community: Moderate Industry	Advanced Community or Military Base
Storage-System Attributes					
Power (kW)	0.5	8	40	400	1 MW
Energy (kWh)	3	45	240	3,600	1.5 MWh
Power					
Base (kW)	0.5	5	10	100	100
Peak (kW)		< 8	< 40	< 400	< 1000
Discharge Duration	5 to 72 hrs	5 to 72 hrs	5 to 24 hrs	5 to 24 hrs	0.5 to 1 hr
Total Projected Number of Systems	47 Million	137,000	40,000	84,000	131,000
Fraction of Market Captured by Storage	> 50	> 50	~ 30	~ 10	< 5
Total Number of Storage Systems to Capture Market Share	24 Million	69,000	12,000	8,000	< 7,000

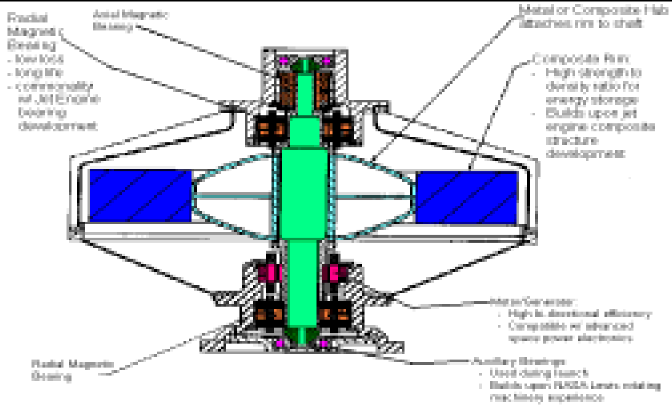
Technology Performance

Advanced Batteries Characteristics Source: DOE Energy Storage Systems Program Annual Peer Review FY01, Boulder City Battery Energy Storage, November 2001.

Energy Storage System	Sodium Sulfur	Vanadium Redox	Zinc Bromine
Field Experience	Over 30 Projects, 25 kW to 6 MW, Largest 48 MW	Several Projects 100kW to 3 MW (pulse power), Largest 1.15 MWh	Several Projects, 50 kW to 250 kW, Largest 400 kWh
Production Capacity	160 MWh/yr	30 MWh/yr	40 to 70 MWh/yr
Actual Production	50 MWh/yr	10 MWh/yr	4.5 MWh/yr
Life	15 yrs	7 to 15 yrs	10 to 20 yrs
Efficiency	72%	70to 80 %	65 to 70%
O&M Costs	$32.5k/yr	$50k/yr	$30 to $150k/yr

Advanced Energy Storage

Technology Description



Flywheel Cutaway

The U.S. electric utility industry has been facing new challenges with deregulation and limitations on installing new transmission and distribution equipment. Advanced storage technologies under active development, in addition to advanced batteries, include processes that are mechanical (flywheels, pneumatic storage) and purely electrical (supercapacitors, super conducting magnetic storage), and compressed-air energy storage. These advanced energy-storage solutions will help achieve more reliable and low-cost electricity storage.

System Concepts

Flywheels (Low-Speed and High-Speed)

Flywheels store kinetic energy in a rotating mass. The amount of stored energy is dependent on the speed, mass, and configuration of the flywheel. They have been used as short-term energy storage devices for propulsion applications such as engines for large road vehicles. Today, flywheel energy storage systems are usually categorized as either low-speed or high-speed. High-speed wheels are made of high strength, low-density composite materials, making these systems considerably more compact than those employing lower-speed metallic wheels. However, the low-speed systems are still considerably less expensive per kWh.

Supercapacitors

Supercapacitors are also known as Electric Double Layer Capacitors, pseudocapacitors, or ultracapacitors. Charge is stored electrostatically in polarized liquid layers between an ionically conducting electrolyte and a conducting electrode. Though they are electrochemical devices, no chemical reactions occur in the energy-storage mechanism. Since the rate of charge and discharge is determined solely by its physical properties, an ultracapacitor can release energy much faster (i.e., with more power) than a battery, which relies on slow chemical reactions. Ultracapacitors deliver up to 100 times the energy of a conventional capacitor and deliver 10 times the power of ordinary batteries.

Compressed-Air Energy Storage (CAES)

CAES systems store energy by compressing air within a reservoir using off peak/low cost electric energy. During charging, the plant's generator operates in reverse – as a motor – to send air into the reservoir. When the plant discharges, it uses the compressed air to operate the combustion turbine generator. Natural gas is burned during plant discharge in the same fashion as a conventional turbine plant. However, during discharge, the combustion turbine in a CAES plant uses all of its mechanical energy to generate electricity; thus, the system is more efficient. CAES is an attractive energy-storage technology for large-scale storage.

Superconducting Magnetic Energy Storage (SMES)

SMES systems store energy in the magnetic field created by the flow of direct current in a coil of superconducting material. SMES systems provide rapid response to either charge or discharge, and their available energy is independent of their discharge rate. SMES systems have a high cycle life and, as a result, are suitable for applications that require constant, full cycling and a continuous mode of operation. Micro-SMES devices in the range of 1 to 10 MW are available commercially for power-quality applications.

Representative Technologies

- While the system-concepts section addressed energy-storage components exclusively, all advanced storage systems require power conditioning and balance of plant components.
- For vehicle applications, flywheels, CAES, and ultracapacitors are under development.
- A dozen companies are actively developing flywheels. Steel, low-speed flywheels, are commercially available now; composite, high-speed flywheels are rapidly approaching commercialization.
- Pneumatic storage (CAES) is feasible for energy storage on the order of 100's MWh.
- Prototype ultracapacitors have recently become commercially available.

Technology Applications

- Energy available in SMES is independent of its discharge rating, which makes it very attractive for high power and short time burst applications such as power quality.
- SMES are also useful in transmission enhancement as they can provide line stability, voltage and frequency regulation, as well as phase angle control.
- Flywheels are primarily used in transportation, defense, and power quality applications.
- Load management is another area where advanced energy-storage systems are used (e.g., CAES). Energy stored during off-peak hours is discharged at peak hours, achieving savings in peak energy, demand charges, and a more uniform load.
- Load management also enables the deferral of equipment upgrades required to meet an expanding load base which typically only overloads equipment for a few hours a day.
- Ultracapacitors are used in consumer electronics, power quality, transportation, and defense and have potential applications in combination with distributed generation equipment for following rapid load changes.

Current Status

- Utilities require high reliability, and per-kilowatt costs less than or equal to those of new power generation ($400–$600/kW). Compressed gas energy storage can cost as little as $1–$5/kWh. SMES has targets of $150/kW and $275/kWh. Vehicles require storage costs of $300 to $1,000/kWh to achieve significant market penetration. The major hurdle for all storage technologies is cost reduction.
- Ultracapacitor development needs improved energy density from the current 1.9 W-h/kg for light-duty hybrid vehicles.
- Low-speed (7,000-9,000 rpm) steel flywheels are commercially available for power quality and UPS applications.
- There is one 110-MW CAES facility operated by an electric co-op in Alabama.
- ix SMES units have been installed in Wisconsin to stabilize a ring transmission system.

Representative Current Manufacturers

Flywheels	Supercapacitors	CAES	SMES
Active Power American Flywheel Systems Pillar	Nanolab Cooper Maxwell NEC	Ingersoll Rand ABB Dresser-Rand Alstrom	American Superconductor

Technology Future
• Developments in the vehicular systems will most likely crossover into the stationary market.
• High-temperature (liquid-nitrogen temperatures) superconductors that are manufacturable and can carry high currents could reduce both capital and operating costs for SMES.
• High-speed flywheels need further development of fail-safe designs and/or lightweight containment. Magnetic bearings will reduce parasitic loads and make flywheels attractive for small uninterruptible power supplies and small energy management applications.
• Much of the R&D in advanced energy storage is being pursued outside the United States, in Europe, and Japan. U.S. government research funds have been very low, relative to industry investments. One exception has been the Defense Advanced Research Programs Agency, with its flywheel containment development effort with U.S. flywheel manufacturers, funded at $2 million annually. The total DOE Energy Storage Program budget hovers in the $4 million to $6 million range during the past 10 years.

Advanced Energy Storage

Market Data

Market Predictions

Source: Sandia National Laboratories, Cost Analysis of Energy-Storage Systems for Electric Utility Applications, February 1997.

Energy-Storage System	Present Cost	Projected Cost Reduction
SMES	$54,000/MJ	5-10%
Flywheels	$200/kWh	443

Technology Performance

Energy-Storage Costs and Efficiencies

Source: Sandia National Laboratories, Characteristics and Technologies for Long- vs. Short-Term Energy Storage, March 2001.

Energy-Storage System	Energy-Related Cost ($/kWh)	Power Related Cost ($/kW)	Balance of Plant ($/kWh)	Discharge Efficiency
Micro-SMES	72,000	300	10,000	0.95
Mid-SMES	2,000	300	1,500	0.95
SMES	500	300	100	0.95
Flywheels (high-speed)	25,000	350	1,000	0.93
Flywheels (low-speed)	300	280	80	0.9
Ultracapacitors	82,000	300	10,000	0.95
CAES	3	425	50	0.79

Technology Performance

Energy-Storage Technology Profiles

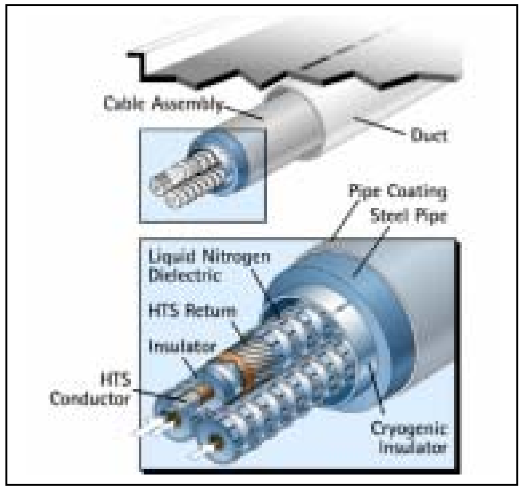
Source: DOE/EPRI, *Renewable Energy Technology Characterizations,* EPRI TR-109496, 1997*,* Appendix A.

Technology	Installed U.S. Total	Facility Size Range	Potential/Actual Applications
Flywheels	1-2 demo facilities, no commercial sites. In 2002, steel flywheels with rotational speeds of 7000-9000 rpm are commercially available for power quality and UPS applications.	kW scale	Electricity (Power Quality) Transportation, Defense
SMES	5 facilities with approx. 30 MW in 5 states	From 1-10 MW (micro-SMES) to 10-100 MW	Electricity (T&D, Power Quality)
Ultracapacitors	Millions of units for standby power; 1 defense unit	7-10 W commercial 10-20 kW prototype	Transportation Defense Consumer Electronics Electricity (Power Quality)
CAES	110 MW in Alabama	25 MW to 350 MW	Electricity (Peak-shaving, Spinning Reserve, T&D)

Superconducting Power Technology

Technology Description

Superconducting power technology refers to electric power equipment and devices that use superconducting wires and coils. High Temperature Superconductivity (HTS) enables electricity generation, delivery, and end use without the resistance losses encountered in conventional wires made from copper or aluminum. HTS wires have the potential to carry 100 times the current without the resistance losses of comparable diameter copper wires. HTS power equipment, such as motors, generators, and transformers, has the potential to be half the size of conventional alternatives with the same power rating and only half the energy losses.



Source: American Superconductor

System Concepts

- HTS systems will be smaller, more efficient, and carry more power than a similarly rated conventional system.
- HTS systems will help the transmission and distribution system by allowing for greater power transfer capability, increased flexibility, and increased power reliability.

Representative Technologies

Transmission Cables	Current Limiters
Motors	Transformers
Generators	Flywheel Electricity Systems

Technology Applications

- Superconducting technology will modernize the electric grid and infrastructure, resulting in greater flexibility, efficiency, and cost effectiveness.
- Wire and Coils have reached a sufficient level of development to allow for their introduction into prototype applications of HTS systems such as motors, generators, transmission cables, current limiters, and transformers.
- Motors rated greater than 1,000 hp will primarily be used for pump and fan drives for utility and industrial markets.
- Current controllers will perform as a fast sub-cycle breaker when installed at strategic locations in the transmission and distribution system.
- Flywheel electricity systems can be applied to increase electric-utility efficiency in two areas—electric-load leveling and uninterruptible power systems (UPS) applications.
- Transformers are environmentally friendly and oil-free, making them particularly useful where transformers previously could not be sited, such as in high-density urban areas or inside buildings.
- Reciprocating Magnetic Separators can be used in the industrial processing of ores, waste solids, and waste gases, as well as performing isotope separations and water treatment.

Current Status

- Much of the research and development in HTS is focused on wire and system development and prototype system design and deployment.
- There are 18 manufacturers, eight National Laboratories, six utilities, and 17 universities participating in the U.S. Department of Energy Superconductivity Program alone. The list of manufacturers includes:

3M	ABB
American Superconductor	Pirelli Cables North America
IGC SuperPower	Waukesha Electric Systems
Southwire Company	

- Prototype power transmission cables have been developed and are being tested by two teams led by Pirelli Cable Company and Southwire Company respectively.
- A 1,000-horsepower prototype motor was produced and tested by Rockwell Automation/Reliance Electric Company. The results of these tests are being used to design a 5,000 hp motor.
- A team led by General Electric has developed a design for a 100 MW generator.
- A 15 kV current controller was tested at a Southern California Edison substation in July 1999.
- The design of a 3 kW/10 kWh flywheel system has been completed. The superconducting bearings, motor/generator, and control system have been constructed and are undergoing extensive testing. A rotor construction is underway.
- The design of the reciprocating magnetic separator has been finalized, and components for the system have been procured and assembled. The test site has been prepared, and cryogenic testing has begun.

Technology History

- In 1911, after technology allowed liquid helium to be produced, Dutch physicist Heike Kammerlingh Onnes found that at 4.2 K, the electrical resistance of mercury decreased to almost zero. This marked the first discovery of superconducting materials.
- Until 1986, superconductivity applications were highly limited due to the high cost of cooling to such low temperatures, which resulted in costs higher than the benefits of using the new technology.
- In 1986, two IBM scientists, J. George Bednorz and Karl Müller achieved superconductivity on lanthanum copper oxides doped with barium or strontium at temperatures as high as 38 K.
- In 1987, the compound $Y_1Ba_2Cu_3O_7$ (YBCO) was given considerable attention, as it possessed the highest critical temperature at that time, at 93 K. In the following years, other copper oxide variations were found, such as bismuth lead strontium calcium copper oxide (110 K), and thallium barium calcium copper oxide (125 K).
- In 1990, the first (dc) HTS motor was demonstrated.
- In 1992, a 1-meter-long HTS cable was demonstrated.
- By 1996, a 200-horsepower HTS motor was tested and exceeded its design goals by 60%.

Technology Future

Year of 50% Market Penetration

Motors	Transformers	Generators	Underground Cable
2018	2015	2019	2013

Source: ORNL - High Temperature Superconductivity: The Products and Their Benefits, 2002 Edition, Table ES-1.

- Low-cost, high-performance YBCO Coated Conductors will be available in 2005 in kilometer lengths.
- The present cost of HTS wire is $300/kA-m. By 2005, for applications in liquid nitrogen, the wire cost will be less than $50/kA-m; and for applications requiring cooling to temperatures of 20-60 K, the cost will be less than $30/kA-m.
- By 2010, the cost-performance ratio will have improved by at least a factor of four. The cost target is $10/kA-m.

Superconducting Power Technology

Market Data

Projected Market for HTS devices (Thousands of Dollars)	*Source: Oak Ridge National Laboratory - High Temperature Superconductivity: The Products and Their Benefits, 2002 Edition, Total Market Benefits, p 40.*								
	2004	**2006**	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**
Motors	0	0	27.29	169.24	527.03	1310.49	3103.37	6360.31	11322.83
Transformers	0	3.8	14.22	37.47	90.63	197.73	371.87	605.23	877.71
Generators	0	0	0	4.09	15.56	41.12	101.16	224.26	426.61
Cables	0	0.17	0.59	1.44	2.81	4.86	7.7	11.21	15.17
Total	0	3.97	42.1	212.24	636.03	1554.2	3584.1	7201.01	12642.32

The report assumes electrical generation and equipment market growth averaging 2.5% per year through 2020. This number was chosen based on historic figures (the past fifteen years) and the assumption that electric demand will drive electric supply.

Underground Power Cables: Market Penetration and Benefits	*Source: Oak Ridge National Laboratory - High Temperature Superconductivity: The Products and Their Benefits, 2002 Edition, Total Market Benefits, p 40.*								
	2004	**2006**	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**
% Market	0	6.7	15	27	40	56	69	77	80
Miles Sold this Year	0	13.89	32.68	61.77	96.19	141.47	183.15	214.73	234.35
Total Miles Installed	0	20.76	74.69	183.34	356.96	616.74	963.04	1379.11	1839.26
Total Annual Savings (10^6 $)	0	0.17	0.59	1.44	2.81	4.86	7.7	11.21	15.17

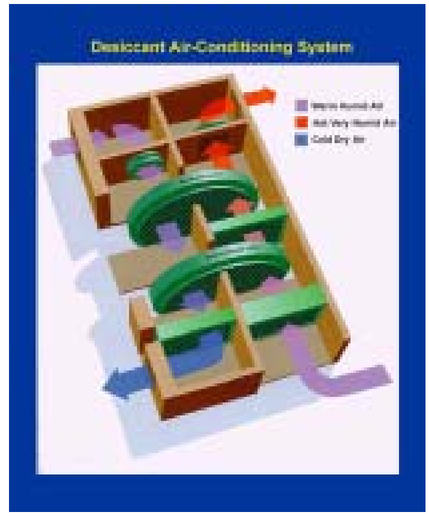
Technology Performance

HTS Energy Savings (GWh)	*Source: Oak Ridge National Laboratory - High Temperature Superconductivity: The Products and Their Benefits, 2002 Edition, Tables M-2, T-1, G-1, C-2*								
	2004	**2006**	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**
Motors	0	0	0.4	3	8	21	48	98	172
Transformers	0	0.1	0.2	1	1	3	6	9	14
Generators	0	0	0	0.1	0.2	1	2	3	6
Cables	0	3	18	56	133	270	488	806	1,236
Total	0	4	19	60	143	294	544	916	1,428

Thermally Activated Technologies

Technology Description

Thermally Activated Technologies (TATs), such as heat pumps, absorption chillers, and desiccant units, provide on-site space conditioning and water heating, which greatly reduce the electric load of a residential or commercial facility. These technologies can greatly contribute to system reliability.



System Concepts

- TATs may be powered by natural gas, fuel oil, propane, or biogas, avoiding substantial energy conversion losses associated with electric power transmission, distribution, and generation.
- These technologies may use the waste heat from on-site power generation and provide total energy solutions for onsite cooling, heating, and power.

Representative Technologies

- Thermally activated heat pumps can revolutionize the way residential and commercial buildings are heated and cooled. This technology enables highly efficient heat pump cycles to replace the best natural gas furnaces, reducing energy use as much as 50%. Heat pumps take in heat at a lower temperature and release it a higher one, with a reversing valve that allows the heat pump to provide space heating or cooling as necessary. In the heating mode, heat is taken from outside air when the refrigerant evaporates and is delivered to the building interior when it condenses. In the cooling mode, the function of the two heat-exchanger coils is reversed, so heat moves inside to outside.
- Absorption chillers provide cooling to buildings by using heat. Unlike conventional electric chillers, which use mechanical energy in a vapor-compression process to provide refrigeration, absorption chillers primarily use heat energy with limited mechanical energy for pumping. The chiller transfers thermal energy from the heat source to the heat sink through an absorbent fluid and a refrigerant. The chiller achieves its refrigerative effect by absorbing and then releasing water vapor into and out of a lithium bromide solution. In the process, heat is applied at the generator and water vapor is driven off to a condenser. The cooled water vapor then passes through an expansion valve, reducing the pressure. The low-pressure water vapor then enters an evaporator, where ambient heat is added from a load and the actual cooling takes place. The heated, low-pressure vapor returns to the absorber, where it recombines with lithium bromide and becomes a low-pressure liquid. This low-pressure solution is pumped to a higher pressure and into the generator to repeat the process.
- Desiccant equipment is useful for mitigation of indoor air-quality problems and for improved humidity control in buildings. The desiccant is usually formed in a wheel made up of lightweight honeycomb or corrugated material (see figure). Commercially available desiccants include silica gel, activated alumina, natural and synthetic zeolites, lithium chloride, and synthetic polymers. The wheel is rotated through supply air, usually from the outside, and the material naturally attracts the moisture from the air before it is routed to the building. The desiccant is then regenerated using thermal energy from natural gas, the sun, or waste heat.

Technology Applications

- Thermally activated heat pumps are a new generation of advanced absorption cycle heat pumps that can efficiently condition residential and commercial space. Different heat pumps will be best suited for different applications. For example, the GAX heat pump is targeted for northern states because of its superior heating performance; and the Hi-Cool heat pump targets the South, where cooling is a priority.
- Absorption chillers can change a building's thermal and electric profile by shifting the cooling from an electric load to a thermal load. This shift can be very important for facilities with time-of-day electrical rates, high cooling-season rates, and high demand charges. Facilities with high thermal loads, such as data centers, grocery stores, and casinos, are promising markets for absorption chillers.
- Desiccant technology can either supplement a conventional air-conditioning system or act as a standalone operation. A desiccant can remove moisture, odors, and pollutants for a healthier and more comfortable indoor environment. Facilities with stringent indoor air-quality needs (schools, hospitals, grocery stores, hotels) have adapted desiccant technology.
- CHP applications are well suited for TATs. They offer a source of "free" fuel in the form of waste heat that can power heat pumps and absorption chillers, and regenerate desiccant units.

Current Status

Thermally activated heat pump technology can replace the best natural gas furnace and reduce energy use by as much as 50%, while also providing gas-fired technology.
Desiccant technology may be used in pharmaceutical manufacturing to extend the shelf life of products; refrigerated warehouses to prevent water vapor from forming on the walls, floors, and ceilings; operating rooms to remove moisture form the air, keeping duct work and sterile surfaces dry; and hotels, to prevent buildup of mold and mildew.
Companies that manufacture TAT equipment include:

York International	Broad
Trane	Air Technology Systems
Munters Corporation	American Power Conversion Company
Kathabar Systems	Goettl

Technology History

- In the 1930s, the concept of dehumidifying air by scrubbing it with lithium chloride was introduced, paving the way for development of the first desiccant unit.
- In 1970, Trane introduced a mass-produced, steam-fired, double-effect $LiBr/H_2O$ absorption chiller.
- In 1987, the National Appliance Energy Conversion Act instituted minimum efficiency standards for central air-conditioners and heat pumps.

Technology Future

- Expand the residential market of the second-generation Hi-Cool residential absorption heat pump technology to include markets in southern states; the targeted 30% improvement in cooling performance can only be achieved with major new advancements in absorption technology or with an engine-driven system.
- Work in parallel with the first-generation GAX effort to determine the most attractive second-generation Hi-Cool technology.
- Fabricate and test the 8-ton advanced cycle VX GAX ammonia/water heat pump.
- Fabricate and test the 3-ton complex compound heat pump and chiller.
- Develop, test, and market an advanced Double Condenser Coupled commercial chiller, which is expected to be 50% more efficient than conventional chillers.
- Assess new equipment designs and concepts for desiccants using diagnostic techniques, such as infrared thermal performance mapping and advanced tracer gas-leak detection.